BLM LIBRARY
88015524

PB 196 083

NONFUEL MINERAL RESOURCES OF [redacted] THE PUBLIC LANDS. VOLUME V: THE NONFUEL MINERAL RESOURCES OF THE UNITED STATES AND THE UTILIZATION OF NONFUEL MINERAL RESOURCES

George F. Leaming, et al

Arizona University
Tucson, Arizona

December 1970

SURPLUS
to
Library Needs

NATIONAL TECHNICAL INFORMATION SERVICE

Distributed ... 'to foster, serve and promote the nation's economic development and technological advancement.'

U.S. DEPARTMENT OF COMMERCE

This document has been approved for public rele sale.

LIBRARY
Bureau of Reclamation
Denver, Colorado

Bureau of Land Management
Library
Bldg 50, Denver Federal Center
Denver, CO 80225

KF
5602
.N812
v.5
c.1

ENT OF THE INTERIOR
LAND MANAGEMENT
OWER'S CARD
resources of the public lands.
ER
OFFICE
DATE RETURNED
Form 1279-3 (May 1982) (formerly DSC 1279-3a)

#5279099
ID: 88015524

C-1

PB196083

HD
242
.T95
1970
v.5

NONFUEL MINERAL RESOURCES OF THE PUBLIC LANDS

Volume V

The Nonfuel Mineral Resources of the United States and The Utilization of Nonfuel Mineral Resources

A Study Prepared for the
Public Land Law Review Commission

by

The University of Arizona
Tucson, Arizona

Republished with revisions
December 1970

BUREAU OF LAND MANAGEMENT LIBRARY
Denver, Colorado
88015524

Prepared under contract with the Public Land Law Review Commission.

The opinions, findings, conclusions and data expressed in this publication are not necessarily those of the Public Land Law Review Commission.

This publication constitutes only one of a number of sources of information utilized by the Commission in the conduct of its public land study program.

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
Springfield, Va. 22151

519

STANDARD TITLE PAGE FOR TECHNICAL REPORTS

1. Report No. PLLRC-30-5

2. Govt. Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle Nonfuel Mineral Resources of the Public Lands. Volume V: The Nonfuel Mineral Resources of the United States and The Utilization of Nonfuel Mineral Resources.

5. Report Date 12/1/70

6. Performing Organization Code

7. Author(s) The University of Arizona

8. Performing Organization Rept. No. 30

9. Performing Organization Name and Address

Public Land Law Review Commission
1730 K St., N.W.
Washington, D. C. 20006

10. Project/Task/Work Unit No.

11. Contract/Grant No. 68-C-20

12. Sponsoring Agency Name and Address

same as 9 above

13. Type of Report & Period Covered interim

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstracts

The report examines the nonfuel mineral resources and the nature of their use, particularly as they are related to the discovery and development process. It also provides a description and analysis of the changing techniques, technology, and processes involved in the search for, discovery, development and production of minerals.

17. Key Words and Document Analysis. 17a. Descriptors

resources, nonfuel, mineral, public lands

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Distribution Statement available through NTIS

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages

22. Price

NONFUEL MINERAL RESOURCES
AND THE
PUBLIC LANDS

THE NONFUEL MINERAL RESOURCES OF THE UNITED STATES and

THE UTILIZATION OF NONFUEL MINERAL RESOURCES

Prepared for
The United States Public Land Law Review Commission

by

The University of Arizona
Tucson, Arizona

George F. Leaming
Principal Investigator
Willard C. Lacy
Associate Principal Investigator

Frank H. Skelding
Project Officer
for the Public
Land Law Review
Commission

Public Land Law Review Commission

NONFUEL MINERAL RESOURCES OF THE PUBLIC LANDS
Volume V: The Nonfuel Mineral Resources of the United States and
The Utilization of Nonfuel Mineral Resources

The University of Arizona
Tucson, Arizona

Republished with revisions December 1970

TABLE OF CONTENTS

Chapter | Page

FOREWORD vii

1 INTRODUCTION AND BACKGROUND

A. THE PROBLEMS 1
  1. The Public Land Law Review Commission 1
  2. Minerals Related Studies 2

B. THE OBJECTIVES OF THE STUDY 3
  1. The Overall Objectives 3
  2. The Basic Hypotheses 3
  3. Specific Objectives 4

C. THE METHOD OF INVESTIGATION 7
  1. The Basic Organization of the study 7
  2. Scope of the Study 7
  3. Methods of Data Collection and Analysis 8
  4. Presentation of Findings 10

2 BASIC CONCEPTS OF ECONOMIC GEOLOGY

A. THE STUDY OF GEOLOGY 13

B. THE COMPONENTS OF GEOLOGY 15

C. THE PROCESSES OF GEOLOGY 17

D. THE STRUCTURES OF GEOLOGY 21

E. THE TIME OF GEOLOGY 26

F. THE ECONOMICS OF GEOLOGY 28
  1. The Components of Economic Mineral Deposits 28
  2. The Processes of Mineral Deposition 30
  3. The Structures of Mineral Deposition 32
  4. The Age of Mineral Deposits 36

G. SUMMARY 48

3 THE GEOLOGY OF THE UNITED STATES

A. THE GEOLOGY OF THE UNITED STATES 51

B. THE FORMATION OF MINERAL DEPOSITS IN THE UNITED STATES 54
  1. Earliest Mineral Deposition 54
  2. Paleozoic Mineral Deposition 54
  3. Mesozoic Mineral Deposition 56
  4. Cenozoic Mineral Deposition 58

C. SUMMARY 60

Chapter Page

4 THE MINERAL RESOURCES OF THE UNITED STATES

A. KNOWN MINERAL RESOURCES BEFORE 1872 63
1. Early Gold Deposits 63
2. Early Silver Deposits 66
3. Early Lead Deposits 68
4. Early Copper Deposits 68
5. Other Early Mineral Deposits 69
6. Early Mineral Deposit Characteristics 69

B. CHANGES IN MINERAL RESOURCES TO 1947 72
1. Changes in Mineral Deposit Characteristics 72
2. Changes in the Location of Mineral Resources 73

C. CHANGES IN MINERAL RESOURCES SINCE 1947 83
1. Changes in Metallic Mineral Deposits 83
2. Changes in Industrical Minerals Deposits 94
3. Changes in the Grade of Mineral Deposits 96
4. Changes in the Importance of By-Product Minerals 109

D. KNOWN MINERAL RESOURCES IN 1968 119
1. Metallic Mineral Reserve Estimates 119
2. Industrial Minerals Reserve Estimates 119

E. CHANGES IN MINERAL RESOURCES EXPECTED BY 1985 127
1. Changes in Mineral Deposit Characteristics 127
2. Changes in the Economic Grade of Mineral Deposits 128
3. New Sources of Minerals 129

F. SUMMARY 135

5 THE PROBLEMS OF MINERAL RESERVE ESTIMATION

A. CONCEPTS OF MINERAL RESERVES 143
1. Concepts of Mineral Deposits 143
2. Types of Ore Reserves 143

B. INDIVIDUAL PROPERTY ESTIMATES 160
1. Metalliferous Properties 160
2. Industrial Minerals Properties 160

C. NATIONAL MINERAL RESERVE ESTIMATES 165
1. Base Metals Reserve Estimates 165
2. Reserve Estimates for Minor Metals 175
3. Precious Metals Reserves 187
4. Industrial Minerals Reserves 192

D. SUMMARY 198

6 MINERAL RESOURCES ON THE PUBLIC LAND

A. MINERAL PRODUCING DISTRICTS AND PUBLIC LAND AREAS. . . 203

B. MINERAL RESOURCES PRODUCED FROM THE PUBLIC LANDS. . . 219

C. MINERALS RESERVED TO THE UNITED STATES

Chapter Page

7 THE SEARCH FOR MINERALS

A. THE EXPLORATION PROCESS 243
  1. The Purpose of Exploration 243
  2. The Phases of Exploration 243
  3. Exploration Objectives 244

B. MINERALS EXPLORATION BEFORE 1872 251
  1. The Exploration Process 251
  2. Reconnaissance Methods 253
  3. Target Examination and Evaluation 257
  4. Exploration Entities 257
  5. Exploration Costs 260
  6. Principal Minerals Sought 260

C. CHANGES IN MINERAL EXPLORATION TO 1947 263
  1. Methods and Techniques 263
  2. Exploration Entities 266

D. CHANGES IN MINERAL EXPLORATION SINCE 1947 269
  1. Causes of Change 269
  2. New Geophysical Methods 270
  3. Geochemical Exploration Methods 273
  4. Commodity Variations 275
  5. Exploration Entities 279
  6. Types of Deposits Sought 279

E. CURRENT EXPLORATION PRACTICE 289
  1. Regional Reconnaissance 289
  2. Target Area Examination 290
  3. Deposit Evaluation 295
  4. Exploration Entities 296
  5. Exploration Costs 302
  6. Exploration Land Requirements 312
  7. Time Intervals in Exploration 313

F. CHANGES EXPECTED BY 1985 319
  1. Changing Objectives and Methods 319
  2. New Exploration Techniques 321

8 MINERAL DEPOSIT DEVELOPMENT

A. THE DEVELOPMENT PROCESS 327
  1. Components of Mine Development 327
  2. Types of Mine Development 329

B. DEVELOPMENT METHODS IN THE 1800'S 332
  1. Placer Mine Development 332
  2. Underground Mine Development 334
  3. Mineral Development Characteristics 335

Chapter Page

C. CHANGES IN MINERAL DEPOSIT DEVELOPMENT TO 1947 337
1. The Pattern of Large Mine Development 337
2. Development Scale and Costs 338

D. CHANGES IN MINERAL DEVELOPMENT SINCE 1947 339
1. The Development Process 339
2. Development Time Requirements 339
3. Mine Development Costs 349
4. Development Area Requirements 357

E. CHANGES IN MINE DEVELOPMENT EXPECTED BY 1985 359

9 THE PRODUCTION OF MINERAL COMMODITIES

A. THE PRODUCTION PROCESS 361
1. The Phases of Mineral Production 361
2. Mining Operations 361
3. Auxiliary Unit Operations 364
4. Surface Mining Methods 364
5. Other Mining Methods 366
6. Beneficiation Operations 366
7. Advanced Processing Operations 367

B. MINERALS PRODUCTION PRIOR TO 1872 370
1. Phases of Production 370
2. Placer Gold Mining 370
3. Other Precious Metal Mining 372
4. Early Copper Mining 372
5. Early Underground Mining Methods 373
6. Mining and the Environment 377
7. Water and Mining 378
8. Early Beneficiation Methods 379
9. Advanced Processing Methods 383
10. Production Costs 387

C. CHANGES IN MINERAL PRODUCTION TO 1947 388
1. Changes in Mining Methods 388
2. Changes in Copper Mining 390
3. Changes in Iron Mining 391
4. Changes in Precious Metal Mining 392
5. Changes in Mining Other Metals 394
6. Changes in Industrial Minerals Mining 396
7. Changes in Beneficiation 397
8. Changes in Concentration 400
9. Changes in the Advanced Processing of Copper 405
10. Changes in the Advanced Processing of Gold 412
11. Changes in Silver, Lead, and Zinc Extraction 415
12. Changes in the Advanced Processing of Ferrous Metals 417
13. Changes in the Advanced Processing of Other Metals 419
14. Changes in the Advanced Processing of Industrial Minerals 420

Chapter Page

D. CHANGES IN MINERAL PRODUCTION SINCE 1947 424
1. Changes in Mineral Output 424
2. Changes in Mining Methods 424
3. Changes in Underground Operations 441
4. Changes in Surface Mining Operations 443
5. Commodities and Changing Mining Methods 445
6. Changes in Beneficiation Operations 457
7. Changes in Advanced Processing 459

E. CURRENT PRACTICE IN MINERALS PRODUCTION 460
1. Placer Mining 460
2. Underground Mining 463
3. Surface Mining 472
4. Mining by Leaching 474
5. Solution Mining 481
6. Frasch Process Sulfur Mining 482
7. Beneficiation Practice 483
8. Advanced Processing of Industrial Minerals 488
9. Advanced Processing of Metals 490
10. Other Advanced Processes 494
11. Scale of Production 495

F. CHANGES IN MINERAL PRODUCTION TO 1985 500
1. Expected Changes in Mining Operations 500
2. Changes in the Importance of Different Mining Methods 502
3. Changes in Production from the Public Lands 507

FOREWORD

The conduct of this study of the nonfuel mineral resources on the public lands of the United States has involved a number of concepts that warrant explanation and a great many people who merit recognition and the gratitude of the principal investigator. The entire subject of minerals and the public lands is as immense as the public lands themselves. As a result, it was necessary to make some rather arbitrary divisions of labor in order to accomplish the work needed for the purposes of the Public Land Law Review Commission.

The first such division of labor involved the establishment by the Commission of the various separate studies of which this is only one. Although minerals form essentially one this single subjectwas divided basically along commodity lines into studies of energy fuel resources, nonfuel resources, and several legal aspects. Each of these has been covered by a separate report. Of necessity, however, there has been some overlap in the conduct of these studies, and such is the case also in this report. In many respects the facts, problems, and issues of minerals on the public lands transcend the basic commodity distinctions made in both the resources and legal aspects studies. Consequently this report contains some material pertinent to the fuel minerals and also to some of the legal aspects of all minerals on the public lands.

The second division of labor was similar to the first in that commodity criteria were used. Throughout this study, certain mineral commodities have been used to focus the work and the presentation of data. These particular minerals have been used, not only because they themselves are or have been important, but because they also represent broader classes of all nonfuel minerals. Thus, in some instances asbestos and gypsum have been used to represent construction materials in general, and copper has been used frequently as a representative of the base metals. Where such representative commodities have been found to be unrepresentative, the exceptions have been noted.

The third division of labor involved geographic criteria. Arizona and the Southwest are part of the general public land area of the Western United States and as such are relevant to the subject at hand. Arizona and New Mexico in many ways are also typical of the entire Western United States. Furthermore, Arizona and the Southwest are closer to the locale of the study contractor than any other part of the West and thus are more familiar to the principal investigator and most members of the project staff. As a result, in order to perform a maximum amount of research within the constraints necessarily imposed, Arizona and the Southwest have been analyzed in somewhat greater detail than the remainder of the West. Wherever it has been appropriate, however, and wherever conditions in the Southwest have not been typical of the entire West, detailed analyses of other areas have been made. In order to overcome any potential Southwestern bias, a concerted effort has been made to utilize data from all parts of the West and to involve in the study personnel familiar with areas other than the Southwest. It is the firm conviction of the principal investigator that any potential regional bias has been eliminated from the study report.

The final division of labor involved those persons directly engaged in the study and to whom the principal investigator is extremely grateful. The study was handled primarily through the Division of Economic and Business Research of the University of Arizona's College of Business and Public Administration and the Department of Mining and Geological Engineering of the University's College of Mines. The support and assistance provided to the project by Dr. C. William Voris, Dean of the College of Business and Public Administration, and Dr. J. D. Forrester, Dean of the College of Mines, are deeply appreciated. Particular appreciation is due Dr. David E. Shirley, Director of the Division of Economic and Business Research, and Dr. Willard C. Lacy, Head of the Department of Mining and Geological Engineering, who also served as associate principal investigator.

A major portion of the research concerned with the geological aspects of the nation's mineral resources was performed under a subcontract by E. Wisser and Associates, and special acknowledgement should be made to Dr. Edward Wisser, Dr. Thomas Nye, and Charles Sewell of that organization for their efforts. The section of the report concerned with mineral resource utilization was largely the result of the combined work of Dr. Lacy and his associates, namely Professors William C. Peters, Jay Dotson, Thomas O'Neil, and Robert O'Haire, as well as visiting Professor Arthur C. Todd who did much of the related historical research. Their contributions are most gratefully appreciated. Several members of the faculty of the University's Department of Economics participated in various portions of the study and the efforts of these men, Professors Philip Bryson, Steven Barsby, and Dennis Cox, should also be recognized.

Probably the greatest share of the research that has gone into this study was performed by a sizeable staff of highly competent student assistants, and the principal investigator is especially appreciative of the efforts of these contributors, namely, James M. Broer, Charles Cartmill, Roy M. Claridge, Karen Daub, Joel Perry, Harry Winters, Carl Winter, Patricia A. Berlat, Suzanne Whitehead, Gene Voorhees, Bruce Ward, Timothy Houck, Richard C. Moores, Ronald Bresnahan, Edward Czekaj, Thomas Porter, Grady Wilson, Howard Blitz, Dennis Benusa, and Janet Moench. In the process of the research, the availability and orderly compilation of reference materials became of vital importance, and so particular thanks are also due to Mrs. Christine Denton and Mrs. Pat Wiedhopf of the Division's Reference Section and to Mr. Constantine Siavelis and Miss Susan Innes who assisted in the compilation of bibliographical information as well as to Mr. Charles P. Armstrong who developed, in conjunction with the Computer Center of the University of Arizona, a computer program for the retrieval of subject references.

The subject matter of the study was such that graphic presentation was almost a necessity in the analysis of the data as well as in the preparation of this final report. The principal investigator was indeed fortunate in having the services of a group of exceptionally skilled young people in the performance of this part of the work, and particular thanks are due to Mr. Theodore Weller, Mr. Marty Van Duyn, Mrs. Mary Chavez, Mr. Edwin Barr, and Mr. Steve Bahre. A profound debt is also owed to Mrs. Evelyn Van Dyke and her secretarial staff in the Division of Economic and Business Research, and expecially to Mrs. Donna Kent and Mrs. LaRene Perkins, who, assisted principally by Misses Gay Kay, Jaydene Haines, Brenda Ravenscroft, and Catherine Trezza, were responsible for the bulk of the typing and secretarial chores associated with the project. Particular acknowledgment and thanks should also be accorded to Mrs. Betty James who was responsible for the final editing of the study manuscript, assisted by Miss Marily Ansell.

The principal investigator also acknowledges that a a particularly strong share of credit for the results of this study should go to Mr. Frank H. Skelding of the staff of the Public Land Law Review Commission for his direct assistance in the project, for his guidance and his patience. For the latter, a grateful dept is also owed to the principal investigator's family.

George F. Leaming
Principal Investigator

Tucson, Arizona
July, 1969

(followed by 1)

CHAPTER 1

INTRODUCTION AND BACKGROUND

A. THE PROBLEM

1. The Public Land Law Review Commission

The Public Land Law Review Commission was established by the Congress of the United States in September, 1964.[1] The Commission was charged with the statutory responsibility for studying the existing laws and regulations governing the retention, management, and disposition of the public lands of the United States. It was also ordered to review the policies and practices of the federal agencies that have been charged with administrative jurisdiction over the public lands insofar as their policies and practices are related to the retention, management, and disposition of the public lands. The Commission was also given the specific task of compiling the data necessary to understand and determine the various demands on the public lands which now exist and which are likely to exist within the foreseeable future.

Section 10 of Public Law 88-606 required the Commission to study and submit recommendations with regard to all of those federal lands that included: (1) the public domain of the United States; (2) reservations (other than Indian reservations) created from the public domain; (3) lands permanently or temporarily withdrawn, reserved, or withheld from private appropriation and disposal under the public land laws (including the mining laws); (4) outstanding interests of the United States in lands that had been patented, conveyed in fee or otherwise, under the public land laws (and including the special problem of reserved mineral rights); (5) national forests; (6) wildlife refuges and game ranges; and (7) the surface and subsurface resources of all such lands, including the mineral resources under the control of the United States in the outer continental shelf.

In order to assist the Public Land Law Review Commission in carrying out the declared policy of the Congress that the public lands of the United States should be either retained and managed or disposed of in such a manner as to provide the maximum benefit for the general public, and in meeting its specific statutory obligations of the Commission, a series of studies regarding various aspects of public land policy were developed.

2. Minerals Related Studies

The Public Land Law Review Commission has designed almost three dozen specific studies and analyses to be performed by independent contractors, by consultants, and by the executive staff of the Commission itself. Three of these studies form a basic background for the problems of mineral resources on the public lands. The first is a *History of Public Land Law Development*[2] and the second is a *Digest of Public Land Laws.*[3] The third study that also provides important background data for a number of aspects of nonfuel minerals utilization on the public lands of the United States involves a forecast of the consumption of all commodities producible on the public lands for the period from 1980 to 2000.[4]

A number of other studies have been developed by and for the Commission that are of greater specific relevance to the policies concerning the nonfuel mineral resources on the public lands. Probably the most relevant (other than this study, of course) is a legal study of nonfuel mineral resources of the public lands involving a study of the federal mining and related laws.[5] Also closely related to the problems of nonfuel mineral resources is the study of the energy fuel mineral resources.[6] A number of other legal studies also bear directly upon the problems of nonfuel minerals on the public lands. One of these is a legal study of coal resources on the public lands,[7] and another is a legal study of the federal oil and gas leasing system.[8] A third is a legal study of oil shale on the public lands.[9] A legal study of geothermal steam resources of the public lands[10] also has particular, though not general, relevance for nonfuel minerals. A further resource study of specific import to some of the problems of nonfuel mineral resources is that concerning the outer continental shelf lands of the United States.[11]

In addition to those studies concerned directly with the legal aspects of the various subsurface resources of the public land areas, there have been a number of other natural resource studies of specific and sometimes limited relationship to the problems of nonfuel mineral resources. These include a study of outdoor recreation on the public lands,[12] a study of the forage resources of the public lands,[13] a study of the timber resources of the public lands,[14] a study regarding the water resources of the public lands,[15] and a study of the administrative procedures used with respect to the public lands.[16] These other studies and the administrative procedures study are related to the problems of nonfuel mineral resources on the public land primarily through the concept of multiple land use.

In effect none of the more than 30 studies programmed by the Commission is completely independent from the problems and policies of nonfuel mineral resources on the public lands. Even a study such as the one on revenue sharing and payments in lieu of taxes[17] has definite bearing on the nonfuel minerals policy for the public lands, because some payments in lieu of taxes and some revenues from mineral resource royalties and sales are shared and therefore fall into this study's domain. Another study, that on withdrawals and reservations of public domain lands,[18] also has a direct bearing upon the problems of mineral resources, precisely because in many respects those areas withdrawn or reserved have been removed from mineral resource consideration and the remaining amount of public land upon which mineral resources may be said to be in existence has therefore been restricted.

Even such subjects as land grants to states,[19] federal legislative jurisdiction,[20] and regional and local land use planning[21] have aspects which are relevant to public land nonfuel mineral resource policies and problems, even though the nonfuel mineral resources themselves may not receive specific treatment in such studies. This is also true of studies designed to develop criteria for determining the maximum benefit for the general public of federal public land laws,[22] and regarding policies relating to use and occupancy,[23] analyses of user fees and charges for public lands and resources,[24] and others that may seem to be of a limited legal or administrative nature. Even other studies that are concerned with resources that seem rather remote from nonfuel minerals, such as those on fish and wildlife resources[25] and intensive agriculture,[26] also have implications for the problems and policies of mineral resource development and utilization on the public lands of the United States.

The Commission's study of federal land laws and policies in Alaska[27] has direct implications for nonfuel mineral resource policies because many of the problems that are found in Alaska involve nonfuel mineral resources, but the studies most relevant to the problems confronting the nonfuel mineral resources on the public lands are those concerning the other mineral resources, i.e., coal, oil, gas, geothermal steam, and oil shale (in effect, all of the energy fuel resources) and those other natural resources which come in most direct physical contact with the nonfuel mineral resources on the public lands, e.g., water, timber, and forage. While all of these various subjects are interrelated in order to examine each, it is necessary to develop specific analyses with specific emphases. In order that a clearer focus on any one problem might be obtained, it is necessary to treat others as though they are nearby but dim sidelights. Thus, although the interrelationships among the different studies programmed by the Commission and in particular among the eight studies of specific relevance to the mineral resources of the public lands are important, they can be touched upon only lightly in this report and only as they have direct relevance to the specific problems and policies of the nonfuel mineral resources on the public lands.

B. THE OBJECTIVES OF THE STUDY

1. The Overall Objectives

It has been the general objective of the study described in this report to provide certain information requested and required by the Public Land Law Review Commission in order to facilitate the evaluation by the Commission of existing public land policy, laws, and regulations as they affect and are affected by the nonfuel mineral resources and those activities concerned with those resources. More specifically, it has been the purpose of the study to:

(1) provide a general description of the nonfuel mineral resources of the United States with particular reference to those found on public lands in the 11 contiguous Western States;

(2) provide information on the relevant characteristics (both technical and economic) of those industries involved in the exploration for and the development and extraction of nonfuel mineral resources, with particular (but not exclusive) reference to the 11 contiguous Western States;

(3) provide information on the nature and extent of the relationships of the nonfuel mineral industries to the economic environment of the nation and the several states and regions of the Western United States;

(4) provide information on the relationships of the nonfuel mineral industries to the physical, social, and institutional environment, particularly in the Western United States;

(5) provide information on the relationships between the nonfuel mineral industries and other actual and potential uses of the public lands and natural resources;

(6) provide an analysis of the effects of the existing system of public land policy upon the nonfuel mineral industries and other users of the public lands and natural resources; and

(7) provide estimates of the effects of possible alternative public land policies, with particular reference to the effects of such policies upon the nonfuel mineral industries in the Western United States.

2. The Basic Hypotheses

Based on the stated study requirements of the Commission as detailed in the *Request for Proposal* dated May 3, 1968, and in order to more effectively guide the research, several basic hypotheses and numerous specific sub-hypotheses were developed. Each of these basic hypotheses corresponds to a major section of the study requirements outline prepared by the Commission staff.

The first and second basic hypotheses concern the mineral industries and their resource base. The first basic hypothesis is that

> *The important characteristics of the nonfuel mineral resources of the United States, and particularly of the Western United States, have changed measurably since 1860 and since 1947 and can be expected to change further by 1985.*

Second, it was hypothesized that the important technical and economic characteristics of nonfuel mineral resource utilization as related to public land use have also changed. More specifically it was hypothesized that

> *The important technical and economic characteristics of nonfuel mineral exploration, development, and production (as related to public land use) have changed measurably since 1860 and since 1947 and can be expected to change further by 1985.*

The third and fourth major hypotheses concern the relationships of the nonfuel mineral industries to their economic, social, institutional, and physical environments. The third basic hypothesis stated that

> *The roles of the nonfuel mineral industries in the economies of the United States and each of the 11 Western States have changed since 1947.*

The fourth hypothesized that

> *The nonfuel mineral industries have had measurable effects upon several aspects of their physical, social, and institutional environment.*

In each case, emphasis was to be placed on the relationships of the nonfuel mineral industries to their environment since the end of World War II and those relationships expected by 1985. This emphasis was determined partly by assumed relevance and partly by the expected availability of data.

Closely related to these hypotheses concerning environmental relationships was the fifth basic hypothesis which stated that

> *The use of public lands and resources by the nonfuel mineral industries has had measurable effects upon the use of such lands and resources by other activities, and these other activities have also had measurable effects upon the nonfuel mineral industries.*

This last hypothesis was designed to serve as a guide to the research in examining the actions and interactions of nonfuel mineral and other resource users within the economic, social, institutional, and physical environment.

The last three basic hypotheses were developed to be concerned directly with the system of public land policy. The sixth basic hypothesis is that

> *The various private systems of mineral land acquisition and tenure used in the United States have had measurable effects upon the nonfuel mineral industries.*

Seventh, it was hypothesized that

> *Present systems of public land policy have had measurable effects upon the nonfuel mineral industries and other users of the public lands.*

Finally, the eighth hypothesis expected that

> *There are potential alternatives to existing public land policy which would probably have differing effects on the utilization of nonfuel mineral resources.*

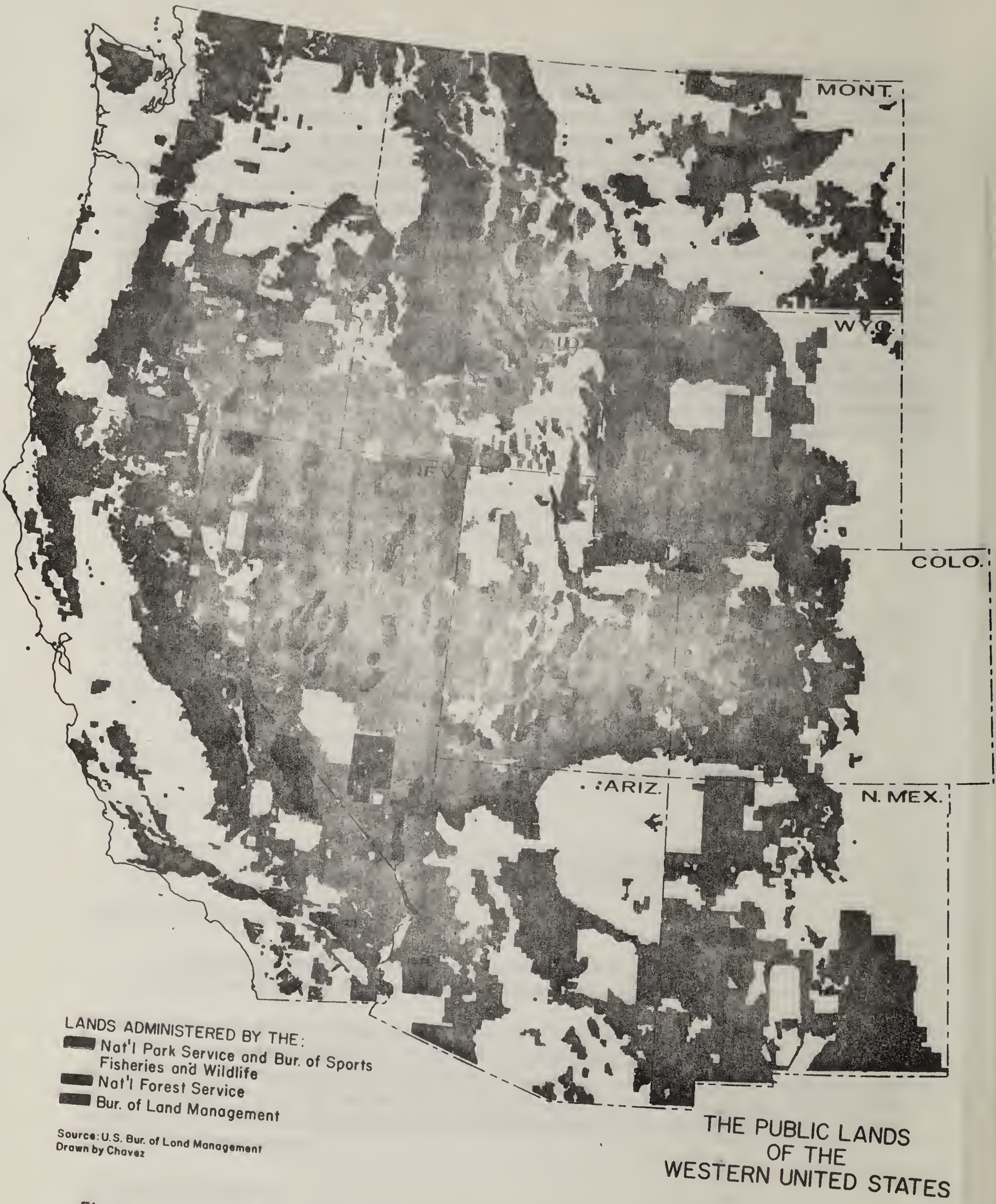
Each of the basic hypotheses stated above then become the focus of a major section of the study. In order to test the basic hypotheses and in order to meet the study requirements as outlined in the Commission's *Request for Proposal*, a number of specific sub-hypotheses were developed. These were stated in the form of specific questions, the answers to which would provide the necessary information relevant to the eight basic hypotheses and the needs of the Commission.

3. Specific Objectives

The primary objective of the study became the testing of the basic hypotheses by providing answers for the detailed questions listed in precise detail in Appendix A and analyzing those answers in the light of the stated purposes of the Public Land Law Review Commission. It thus was not the purpose of the study to develop proposals for public land legislation, but rather to provide factual information and analyses based on fact and experienced judgement relevant to proposals that have been or may be made.

It should be reemphasized that it was not the purpose of the study to "prove" any of the hypotheses as formulated but rather to test them by the proper analysis of the relevant and available data, which could either support them or refute them. Nor was it the purpose of the research to answer all of the specific questions as framed in the affirmative (or negative). It was fully expected that some of the hypotheses as stated would be refuted while others would be supported by the findings of the study. It was also expected that the factual answers to many of the questions as devised would not be as initially anticipated. For some questions it was fully expected that there would be no adequate answer available within the constraints of time and money imposed on the research.

The specific objective of the study, therefore, became one of collecting and analyzing appropriate data to answer the questions asked and to thereby test each of the basic hypotheses developed and stated in accordance with the purposes of the Public Land Law Review Commission.


MONT.
WYO.
ID.
NEV.
COLO.
ARIZ.
N. MEX.
LANDS ADMINISTERED BY THE:
■ Nat'l Park Service and Bur. of Sports Fisheries and Wildlife
■ Nat'l Forest Service
■ Bur. of Land Management
THE PUBLIC LANDS OF THE WESTERN UNITED STATES

Source: U.S. Bur. of Land Management
Drawn by Chavez

Fig. 0 – The public lands of the United States relevant to this study cover large areas of the eleven Western States. Public lands containing nonfuel mineral resources are also found in Alaska and other states.

C. THE METHOD OF INVESTIGATION

1. The Basic Organization of the Study

Initially the study was organized into three major parts: (1) the mineral resources and their utilization; (2) environmental relationships; and (3) minerals in land systems. These major sections were subsequently each divided into several smaller categories along lines suggested by the eight basic hypotheses mentioned in the previous chapter.

The first major section was divided into two parts. The first concerned the mineral resources themselves and was focused on the testing of the first basic hypothesis. The second part dealt with the search for mineral deposits, their development, and utlization. It was focused on the study's second basic hypothesis, i.e., that the technical and economic characteristics of nonfuel minerals exploration and production have changed.

The second major part of the study was also divided into several parts. The first concerned the role of the mineral industries in the economic environment. The second delved into the relationships between the nonfuel mineral resources and industries and various aspects of the physical and social environment. The third involved a study of the relationships between mineral resource users and other users of the public lands. The distinction between the second and third parts in most cases was one of emphasis rather than specific subject matter.

The third and final portion of the study was likewise organized into three principal parts. The first dealt with mineral land systems under non-federal jurisdiction, i.e., on private and state lands. The second involved an analysis of the existing public land system with respect to nonfuel minerals. The third and last part provided an analysis of proposed alternative public land systems.

2. Scope of the Study

It was assumed for purposes of this study that the area of greatest interest for public land policy in relation to the nonfuel mineral industries of the United States is that region of the Western United States comprised of the 11 states of Washington, Oregon, California, Arizona, New Mexico, Colorado, Utah, Nevada, Idaho, Montana, and Wyoming. It was also assumed, however, that other areas of the nation might also have some specific relevance in certain restricted aspects of the study.

It was further assumed that the particular nonfuel mineral industries of greatest relevance for public land policy are those industries involved in the production of the metals, iron, copper, lead, zinc, gold, silver, molybdenum, tungsten, nickel, mercury, beryllium, and uranium, and of the non-metallics, phosphates, potash, sodium compounds, asbestos, and limestone. It was also assumed, however, that certain other minerals, particularly some of the non-metallics, may also be of relevance in certain respects. In addition, it was assumed that the nonfuel mineral industries as defined in total involve the production of other products (e.g., sand and gravel, sulfur, gypsum) which although considered relevant for the purposes of the study were considered to be represented by the specific commodities mentioned previously.

It was assumed for purposes of this study that the most relevant public lands to be studied are those for which the Commission has been made primarily responsible under Section 10 of Public Law 88-606. These are all those federal lands included in: (1) the public domain of the United States; (2) reservations, other than Indian reservations, created from the public domain; (3) lands permanently or temporarily withdrawn, reserved or withheld from private appropriation and disposal under the public land laws, including the mining laws; (4) outstanding interests of the United States (including reserved mineral rights) in lands patented, conveyed in fee or otherwise under the public land laws; (5) national forests; (6) wildlife ranges and refuges; and (7) the surface and subsurface resources of all such lands.

LIBRARY
Bureau of Reclamation
Denver, Colorado

The specific information required for the completion of the study requirements was of four general types. The first consisted of published and other readily available public data (e.g., court or congressional testimony) concerning the public lands and resources, the various relevant economies, the several phases of mineral industry activity, and other public land using activities. Much of this information was available in the extensive reference collection of the Division of Economic and Business Research at The University of Arizona.

The second general type of information required was that compiled by other public agencies, including the Public Land Law Review Commission, itself, and provided to the Contractor. Included in this general category was information available from other studies being done for the Commission.

The third general type of data required was that obtained from private firms operating in the nonfuel mineral industries. Needed information was in fact obtained from a wide variety of mineral industry sources. The fourth general class of information to be utilized was that already available in the extensive personal files of members of the project staff.

Two moderately extensive mail surveys designed to yield primary data from both private and governmental sources were included within the scope of the investigation. Nevertheless, the severe time limitations imposed on the study prevented any substantial development or use of primary information.

The scope of the study was thus confined in several ways. The subject matter was limited first to those lands for which the Commission was primarily concerned. Second, the types of minerals involved were limited to those metallic and non-metallic minerals considered to be the most significant in public land issues and for which appropriate data would be readily available. Third, the breadth and depth of investigation and the sources of data utilized were limited in an attempt to achieve optimum results within the constraints of time and money imposed under the contract.

3. Methods of Data Collection and Analysis

The methods used in the collection and analysis of data varied from one part of the study to another. Some of the variations were slight while others were considerable. In each portion of the study, indeed for each specific question, the methods of data collection and analysis were designed to be most appropriate to the subject matter and to yield a maximum amount of relevant information within a minimum time and at minimum expense. Because both subject matter and data availability varied widely, the methods used also varied in a similar manner.

In the first major part of the study (the portion concerned with resources and their utilization), information of several types was obtained from a variety of sources. A major portion of the data on nonfuel mineral resources and industry technology were taken from the recognized journals in the subject field including *Mining Engineering*, *Economic Geology*, *Engineering and Mining Journal*, *Journal of Exploration Geophysics*, *Mining Congress Journal*, and others. In addition a number of standard textbooks and reference works, including *Geology of the Porphyry Copper Deposits*[28], *Economics of the Mineral Industries*[29], *Industrial Minerals and Rocks*[30], and others, were used. The numerous publications of the United States Geological Survey, the United States Bureau of Mines, and the United States Bureau of the Census, as well as various other agencies of the Departments of Commerce and Interior, were likewise used. A complete list is provided in the bibliographical sections of the study report.

Other sources that were utilized specifically in this portion of the study were the proceedings of special symposia, such as the Symposium on American Mineral Law Relating to Public Land Use (held at The University of Arizona in 1966) and the several symposia on Computers and Computer Applications in Mining and Exploration, sponsored by The University of Arizona, the Colorado School of Mines, Pennsylvania State University and Stanford University, as well as unpublished reprints from professional meetings, many of which were readily available in the private files of members of the research staff.

Selective use was also made of information obtained from individual mining and exploration firms, primarily on the basis of mail questionnaire returns from a limited but representative sample of such firms. A certain number of meetings and direct information requests were also arranged with knowledgeable persons in mining and exploration firms, appropriate government agencies, and professional organizations.

In analyzing the quantitative data obtained in this portion of the study, standard time series analysis and other generally accepted statistical techniques were used. These are described in far greater detail in the methodological appendix. Throughout much of the analysis, however, non-quantitative procedures were used, either because of the qualitative nature of the subject matter or because of the inavailability of adequate quantitative information.

In compiling and analyzing the data necessary to test the specific working hypotheses developed for the second part of the study, extensive use was made of statistical information supplied by the Commission. Such information was supplemented by additional data available in the reference collection of the Division of Economic and Business Research at The University of Arizona. A limited amount of complementary data was also obtained from various state agencies in the 11 Western States.

In analyzing the quantitative information needed to test the validity of the several specific hypotheses, the statistical techniques used were relatively simple. Again, these are described in detail in the statistical appendix provided to explain those techniques used. The selection of the specific techniques to be used in the analysis was made by the principal investigator based upon the characteristics of the data and as deemed appropriate for the testing of the individual hypotheses.

As much as possible, both original data and the analyses of the data have been presented in both tabular and graphic form. Sufficient original data have been presented to support all analyses and answers reached. Wherever extensive amounts of supporting data have tended to detract from the textual and graphic presentations of the research findings, they have been presented in suitable appendices. This practice was followed throughout the entire study.

In compiling and analyzing the information necessary to test the specific working hypotheses involved in the study of the relationships between mineral resources and the physical and social environment, a wide variety of sources was used to provide information of several types. A large proportion of the information was obtained from journals and other standard publications in the fields of mining, geology, geography, forestry, water resources, agronomy, range management, civil engineering, urban planning, land economics, climate and weather, environmental control, and recreation. In addition, direct information requests were made of resource persons in these and related specializations. Available masters' and doctoral theses in these subjects were also reviewed.

Governmental agencies were able to provide considerable amounts of data for this portion of the study. In addition to the publications of various relevant federal and state agencies already available, reviews were made of testimony compiled in Forest Service and Bureau of Land Management hearings, and meetings were held with selected members of those two organizations. Some relevant information was obtained from private organizations such as sportsmen's groups, conservation societies, farmers' organizations, and trade associations, as well as from private firms.

Wherever possible, quantitative analytical techniques were used. Simple descriptive analyses, however, were also appropriate in a number of instances in this section. This included results that were appropriate for presentation in graphic as well as in case study form.

In compiling and analyzing the information necessary to test the specific working hypotheses concerned with the analysis of the present public land system, the primary source of data used was the legal study conducted by Twitty, Sievwright and Mills of Phoenix, Arizona, as well as other portions of this study. The analysis involved in testing the specific hypotheses involved in this section was mostly a matter of simple qualitative comparisons. Again, however, quantitative techniques were used wherever they were considered appropriate.

In compiling and analyzing the information necessary to test the validity of the specific working hypotheses formulated with respect to private land systems (including state land systems), a limited number of widely dispersed sources was used. For the most part, relevant data were obtained from private firms and trade associations, partly by mail questionnaire. These were supplemented by information on state mineral and land laws as obtained from appropriate state agencies throughout the West. Some information was also obtained by direct information requests to selected individuals and from the records of court proceedings and legislative hearings. The analytical techniques employed were largely historical and descriptive. Projections of quantitative data where necessary were made on the basis of widely used forecasting techniques.

In compiling and analyzing the information necessary to test the specific hypotheses relevant to the analysis of alternative systems, the primary sources used were the contractor performing the related legal study, the other portions of this study, the personal judgements of the researchers involved in this study, and other resource persons as deemed appropriate. The data were analyzed using simple comparative, qualitative methods. Wherever possible, the impacts of alternative methods have been expressed in quantitative terms and the bases for estimation concisely explained and made available for use with other alternatives that may be developed after the completion of this study.

4. Presentation of Findings

The results of this study of the nonfuel minerals on the public lands of the United States have been organized into several sections for presentation. This first section includes only introductory material and the background to the problem. The second section presents a discussion of the study's findings regarding the mineral resources themselves. Wherever possible, results have been presented in graphic form with detailed supporting data relegated to the statistical appendix.

The third section of the study includes the material on the utilization of mineral resources and contains chapters on minerals exploration, development, production, and marketing. As in the first section, wherever possible, the results of the research have been presented graphically, with detailed support data provided in the appropriate section of the appendices.

Section four of the study report presents information relevant to the environmental relationships of the mineral industries. This section includes chapters on the economic, physical, social, and institutional environments and on the interrelationships between various users of the public lands. Again, results are presented graphically to the fullest extent possible.

The fifth and final section of the report proper includes the various analyses of the existing land system and proposed alternatives. The sixth section includes all of the report's appendix and bibliographical material as well as a subject index.

FOOTNOTES

1/ Act of September 19, 1964 (78 Stat. 982 as amended, 43 U.S.C. par. 1391-1400).

2/ *History of Public Land Law Development,* Public Land Law Review Commission, Paul Wallace, Gates, Cornell University, and Robert W. Swenson, the University of Utah, Washington, D.C., 1968.

3/ *Digest of Public Land Laws,* Public Land Law Review Commission, Shepards Citations, Inc., Washington, D.C. 1968.

4/ *Projection of the Consumption of Commodities Producible on the Public Lands of the United States 1980-2000,* Robert R. Nathan Associates, Washington, D.C.

5/ *Legal Study of Nonfuel Mineral Resources of the Public Lands* (the Federal Mining Law and related laws), Twitty, Sievwright, and Mills, Phoenix, Arizona.

6/ *Energy Fuel Mineral Resources,* ABT Associates, Cambridge, Massachusetts.

7/ *Legal Study of Coal Resources on Public Lands,* University of Utah.

8/ *Legal Study of the Federal Competitive and Noncompetitive Oil and Gas Leasing Systems,* Rocky Mountain Mineral Law Foundation, Boulder, Colorado.

9/ *Legal Study of Oil Shale on Public Lands,* University of Denver School of Law.

10/ *Legal Study of Geothermal Steam Resources of the Public Lands* Public Land Law Review Commission.

11/ *Outer Continental Shelf Lands of the United States,* Nossaman, Waters, Scott, Krueger and Riordan, Los Angeles, California.

12/ *Outdoor Recreation Use of the Public Lands,* Herman D. Ruth and Associates, Berkeley, California.

13/ *Forage Resource of the Public Lands,* University of Idaho.

14/ *Public Land Timber Policy,* George Banzhaf and Company, Milwaukee, Wisconsin.

15/ *Development, Management, and Use of Water Resources on the Public Lands,* Charles F. Wheatley, Jr., Washington, D.C., Charles E. Cocker, University of Washington, Thomas M. Stetson, San Francisco, California, and Daniel J. Reed, Los Angeles, California.

16/ *Administrative Procedures and the Public Lands,* Colorado State University.

17/ *Revenue Sharing and Payments in Lieu of Taxes,* EBS Management Consultants, Inc., Washington, D.C.

18/ *Withdrawals and Reservations of Public Domain Lands,* Charles F. Wheatley, Jr., Washington, D.C.

19/ *Land Grants to States,* Public Land Law Review Commission.

20/ *Federal Legislative Jurisdiction,* Land and Natural Resources Division, U. S. Department of Justice.

21/ *Regional and Local Land Use Planning,* Herman D. Ruth and Associates, Berkeley, California.

22/ *Criteria to Judge Facts to Determine Maximum Benefit for the General Public,* Public Land Law Review Commission.

23/ *Federal Public Land Laws and Policies Relating to Use and Occupancy,* Daniel, Mann, Johnson, and Mendenhall, Los Angeles, California.

24/ *User Fees and Charges for Public Lands and Resources,* Public Land Law Review Commission.

25/ *Fish and Wildlife Resources on the Public Lands,* Colorado State University.

26/ *Federal Public Land Laws and Policies Relating to Intensive Agriculture,* Kronick, Moskovitz, Tiedemann, and Girard [legal portion], Sacramento, California, and South Dakota State University [resources portion].

27/ *Federal Land Laws and Policies in Alaska,* University of Wisconsin.

28/ Titley, Spencer R. and Carol L. Hicks, *Geology of the Porphyry Copper Deposits,* The University of Arizona Press, Tucson, Arizona, 1966.

29/ Robie, Edward H., *Economics of the Mineral Industries,* 1959, The American Institute of Mining, Metallurgical, and Petroleum Engineers, New York.

30/ Gillson, Joseph L., *Industrial Minerals and Rocks,* 1960, The American Institute of Mining, Metallurgical, and Petroleum Engineers, New York.

CHAPTER 2

BASIC CONCEPTS OF ECONOMIC GEOLOGY

A. THE STUDY OF GEOLOGY

1. Physical Geology

Geology is literally the study of the earth, its surface and its depths, in all its physical aspects. As are most scientific disciplines, geology is itself further divided into a number of basic branches which are in turn divided into more specialized realms. *Physical geology* deals with the physical behavior of the earth, how it was formed, and the processes which have, or have had, effects upon it. *Geophysics* is the more specialized study of the physical properties of the earth (e.g., its vibrations, density, and magnetism), the basic physical forces which affect it (e.g., gravity), and the effects of these forces.

2. Historical Geology

Historical geology deals with the history of the earth as a physical entity. The earth that we know is apparently more than four billion years old, and has had an extremely complex life. At one time or another large portions of what are now the continents were covered by seas or glaciers. Across the face of the earth, vast mountainous regions have been formed and subsequently destroyed through erosion.

The *sedimentary rocks* formed in ages past by chemical precipitation in seas and lakes and by the deposition of transported rock and soil particles, together with the fossilized remains of plants and animals in these rocks, provide a record of these past events. A knowledge of the distribution and thickness of such rocks enbables those geologists interested in the earth's physical history to outline the boundaries of ancient lakes, rivers, and oceans. The character of these sedimentary rocks gives clues to their environment during formation, the sources of the sediments, and the location of ancient mountain chains. The relationships of various sedimentary rock types to each other, their thicknesses, and the types of fossils present in them give evidence of the lengths of time involved and the relative ages of the different rocks. The study of these characteristics is termed *paleontology.*

Historical geology also involves study of the ages of *igneous* and *metamorphic rocks,* whose formation has often been related to periods of mountain building. By measuring the ratios of radioactive elements found in existing rocks to their decay products, an approximation of the absolute ages of these rocks can be made by those concerned with *geochronology.*

3. Mineralogy and Petrology

Mineralogy and *petrology* are concerned with the chemical composition, physical characteristics, nature of formation, occurrence, and atomic structures of minerals and rocks. A *mineral* is defined as an inorganic substance which naturally occurs in the earth's crust and which has a definite chemical composition (or range of compositions) and usually a definite crystalline structure. *Minerals are the component materials of all rocks and soils.*

Petrology involves investigation of the mineral and chemical composition of rocks, and the various chemical and physical processes which led to their formation. A closely related and overlapping field of study is *geochemistry,* which is concerned with the chemistry of the earth and its rocks and minerals, variations in their chemical content and in the chemical processes which form, preserve, transport, or destroy them. Certain types of chemical processes involved in weathering, for example, can cause the formation of economic deposits of copper, nickel, and aluminum. An understanding of the chemistry involved in the formation of specific mineral deposits is thus quite useful in mineral exploration, helping geologists to distinguish favorable and unfavorable environments for specific mineral deposition in amounts adequate to be considered ore.

4. Structural Geology

Structural geology is that branch of geology concerned with the attitudes and positions of rock formations relative to each other, the sequence of events which caused these formations to arrive at their existing configurations, and the forces responsible for these events. The form and attitude of different rock formations and their relationships to each other have frequently changed during different periods of geologic history. Movements of the earth's crust may have tilted originally horizontal rock formations, crumpled them into a series of folds, or ruptured them. Molten rock *(magma)* forcing its way up from the interior of the earth may have arched over-lying, older formations or cut through them along a fracture.

The geologic map is one of the tools of structural geology which shows known rock relationships. Usually not all of the key structural relationships are exposed at the earth's surface, however, and it is often necessary to project the known information and estimate the most logical interpretation of the geologic structure. Many areas are exceedingly complex, leading to several different structural interpretations. Since geologic structures are of prime importance in specific mineral deposit formation, the correct solution of structural puzzles is vital to the discovery of many such mineral deposits.

5. Economic Geology

Mineral deposits are formed, and are found, under a variety of chemical and physical environments. Many specific mineral deposits are characteristically (but not exclusively) associated with particular rock types and structural conditions. The study of *economic geology* involves the theories of formation of different mineral deposits, the environments favorable for their occurrence, and the different methods and techniques of mineral exploration. A broad knowledge and understanding not only of specific mineral deposits themselves but of the other fields of geology, including geophysics and geochemistry, is therefore necessary in economic geology. Geophysical instruments which measure the physical properties of the earth and its response to electrical currents are used to detect structural and mineralogical features sometimes related to economic mineral deposits. Geochemical prospecting normally entails collecting small rock and soil samples over large areas and determining, from assays of the samples, the location of higher-than-normal concentrations of specific elements or minerals. These abnormal concentrations, called *anomalies*, may overlie or be displaced laterally from a subsurface mineral deposit. Economic geology also involves familiarization with mining methods and the economics of the mineral industries in order to evaluate the merits of individual deposits or targets for exploration.

B. THE COMPONENTS OF GEOLOGY

1. Minerals

A *mineral* is, by definition, any naturally-occurring element or inorganic substance having a definite (or variable, within fixed limits) chemical composition and crystalline structure. Deposits of coal, petroleum, and naturally-occurring brines do not fit such a rigorous definition but have, in generic terms, also been considered minerals, principally because they are not readily identifiable as either animal or vegetable. Supplies of groundwater have also been described by some (particularly in portions of the Southwest) to be mineral in character, again principally because water is a naturally-occurring substance found in the earth's crust that is not organic in origin.

2. Rocks

Rocks are solid, cohesive aggregates of one or more types of minerals, which have formed as a result of the various geologic processes. Rocks are classified not only according to their mineral content but also in accordance with their mode of formation, grain size, and physical appearance. For example, the rock called *mudstone,* under proper conditions of compaction, will become a *shale.* Further compaction with greater development of parting planes will change the shale to *slate.* As another example, part of the same magma from which the rock we call *granite* crystallized at depth might have ascended to or near the surface and crystallized as a fine-grained granite equivalent called *rhyolite.*

Rocks are generally classified first by their mode of formation and then by their chemical composition and granular texture. *Igneous* rocks are those that have been formed by the cooling and solidification of *magma* or molten material, either beneath the surface of the earth or after exposure to the atmosphere. *Sedimentary* rocks are those that have been formed by the compaction and solidification of loose mineral and rock particles deposited by the actions of wind, water, chemical reaction, and gravity. *Igneous* and *sedimentary* rocks which have undergone extensive change sufficient to alter their mineral composition are termed *metamorphic rocks.*

All igneous rocks rich in silica, aluminum, sodium, and potassium are called *acidic,* and may be similar to granite or rhyolite in chemical composition. Igneous rocks rich in iron, magnesium, and calcium are called *basic. Basalt* is a fine-grained basic rock usually occurring as a result of volcanic activity, and *gabbro* is the coarse-grained *intrusive* chemical equivalent. *Ultrabasic* igneous rocks are extremely rich in iron and magnesium.

Diorite and *monzonite* are coarse-grained igneous rocks having compositions intermediate between *granite* and *gabbro.* If these intermediate rocks are rich in the mineral *quartz,* they may be called *quartz diorite,* or *quartz monzonite.* Fine-grained volcanic equivalents are *latite, quartz latite, andesite,* and *dacite.* Some intrusive igneous rocks and many volcanic rocks contain scattered coarse-grained minerals surrounded by much finer-grained minerals, like raisins in rice pudding. These rocks are called *porphyries.*

Sedimentary rocks may form in place (e.g., the *laterites*) as residual deposits or they may form where deposited in the bottoms of valleys, river and stream channels, lakes, oceans, swamps, or lagoons. *Evaporite* deposits (e.g., salt, gypsum, trona, and potash) may form in sheltered lagoons or lakes where the rate of evaporation is very high. Some *limestone* formations consist almost entirely of accumulations of calcium carbonate skeletons of animals or plants which lived in water. Coral reefs are an example of this. Other animal and plant life have siliceous skeletons which settle to the bottom of lakes and seas, forming deposits of *diatomaceous earth.* More common sedimentary rocks are those formed from the products of erosion, including *shale* (from mud and clay), *sandstone* (from sand), and *conglomerate* (from gravel).

Metamorphic rocks are designated most often according to their characteristics. Limestones which have been changed to a crystalline form are called *marble.* Shales are frequently metamorphosed into highly foliated rocks known as *schists*. Granitic rocks are most often changed into the fine-grained metamorphic rock known as *gneiss*.

3. Unconsolidated Sediments

Unconsolidated sediments consist of rock particles of all sizes which have been transported from hills and mountains downward into valleys, rivers, lakes, and the oceans. During their transport, rocks are broken into progressively finer particles by abrasion and chemical action. The finer particles are more easily transported and, as a rule, are deposited at greater distances from their source than are coarser particles. The rates of erosion and deposition, however, are never constant. Periods of rapid erosion may cause the formation of deposits containing a large proportion of gravel, which are overlain in quieter periods by sand, silt, or clay. Volcanic ash, diatomaceous earth, and limy mud are also considered as unconsolidated sediments, although the first is produced by igneous activity, the second by living organisms, and the last by chemical precipitation rather than by erosion and deposition.

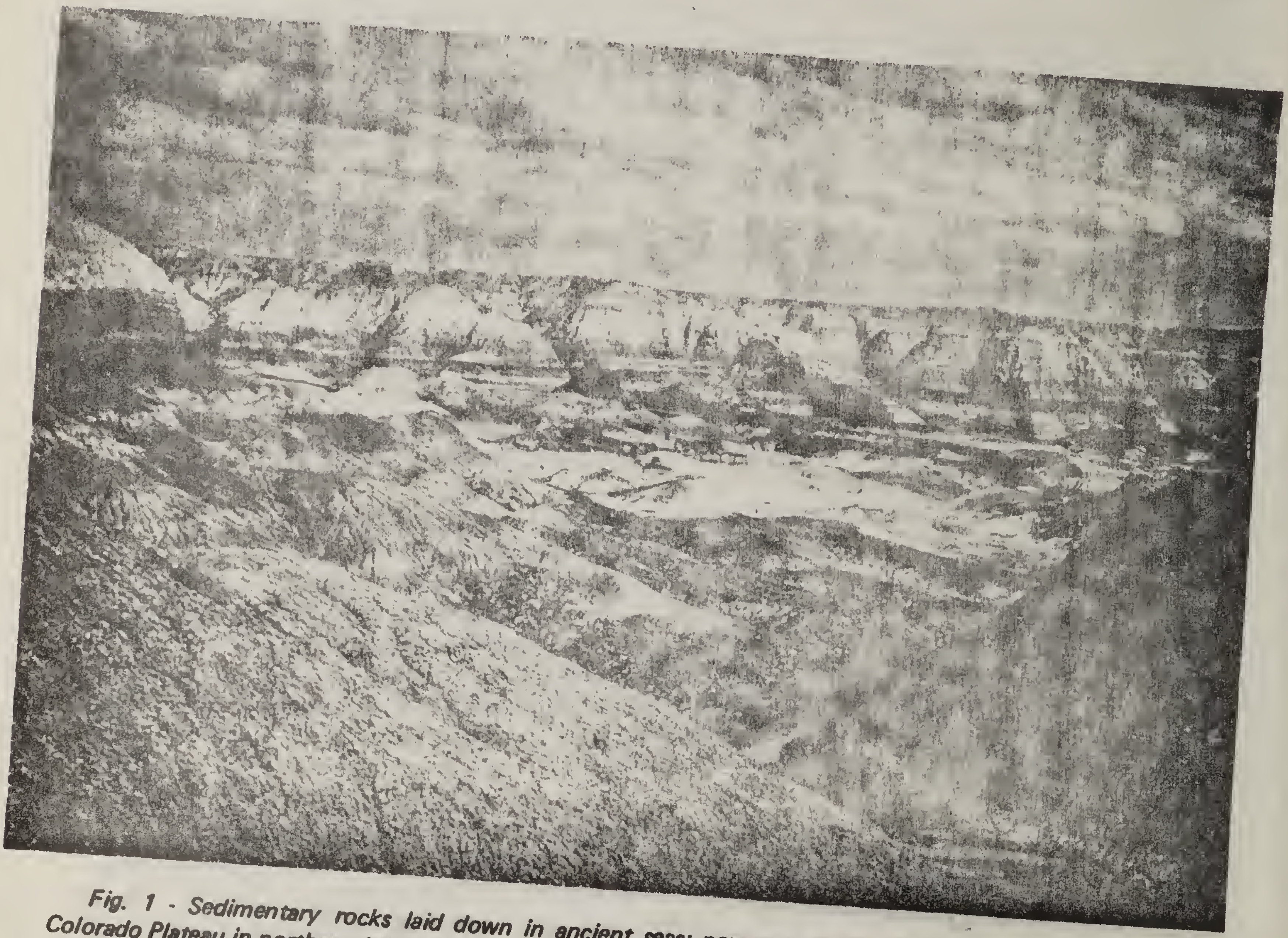


Fig. 1 - Sedimentary rocks laid down in ancient seas; now part of the Painted Desert area of the Colorado Plateau in northern Arizona.

C. THE PROCESSES OF GEOLOGY

1. Igneous Processes

The pressure and temperature of the earth increases gradually with distance below the surface. At depths of several tens of miles, the material which makes up the earth's crust (depending on its composition) may be almost completely molten. This molten material is called *magma*, and normally is less dense than the overlying solid rock. As the magma is subjected to the pressures of overlying material, it may be squeezed upward along weak zones in the earth. This process by which magma penetrates solid rocks is called *intrusion.* Magma which has cooled and solidified is called an *igneous* rock. *Granite* and *basalt* are both igneous rocks, but of different mineral and chemical composition.

Some magma reaches the surface of the earth and pours out, explosively or slowly, from volcanoes or fissures in the earth's crust in the process known as *extrusion.* Upon cooling and solidification, the igneous rocks thus formed are called *volcanic* or *extrusive rocks.* A magma which pours out over the surface is called *lava,* as long as it is molten. Often, however, the magma erupts so rapidly and explosively into the air that it is fragmented into small particles which solidify into *volcanic ash* or *dust.* Larger particles called *cinders* and *volcanic bombs* may also be formed. When the ash settles to the ground, it may in time become compacted into rock, called *tuff.* Not all of the magna associated with volcanic activity pours out over the surface, and some of it cools to rock in the avenue of ascent near the surface, so that *dikes, necks,* and *plugs* of igneous rock are formed.

2. Weathering and Erosion

The decomposition and disintegration of rocks at and near the earth's surface by physical and chemical processes is called *weathering.* The products of weathering are normally carried off by *erosion.* Alternating heat and cold, the expanding action of ice in cracks of rocks, and abrasion by the action of wind-blown sand or by water, all break rocks down physically. Water percolating into the ground dissolves some minerals from the rocks and forms acidic or basic solutions which further attack the rock and break it down chemically.

The action of groundwater is selective under certain conditions, and may leave some elements or minerals in place while altering and removing others. The weathering and subsequent erosion of aluminum- or nickel-bearing rocks may leave *residual* or *secondary* deposits (called *laterities*) of minerals rich in these metals. The process by which minerals are dissolved and carried away in solution is called *leaching.*

The downward slope movements of soil and rock fragments impelled by gravity play an important part in *erosion.* Rocks decomposed and fragmented by weathering are also transported by wind (as sand and dust), by water (in streams, rivers, and ocean currents), and by ice (in glaciers).

The swifter the flow of running water, the larger the rock particles it can carry. Fine clay normally remains suspended in running water, while sand grains and pebbles are pushed along the bottom of a brook or river. Turbulent and rapid stream flows, caused by sudden thunderstorms typical in the Mountain West, have been know to move large boulders considerable distances downstream in a matter of minutes. Strong winds may produce dust and sand storms which transport millions and billions of tons of soil and rock waste. Given enough time, entire mountain chains can be (and have been) leveled.

3. Sedimentation

The products of weathering are moved physically or chemically in solution to sites of deposition. Through chemical *precipitation, evaporation,* or physical *settling,* various types of sediments are thus deposited. The accumulated weight of the sediments over time causes their compaction, and chemical action may cement rock particles together so that in time the sediments are lithified, or converted into *sedimentary rocks*. Sand becomes *sandstone*, clay and silt *mudstone* or *shale*, and limy muds *limestone*. Mixed accumulations of boulders, pebbles, and sand are often lithified to become *conglomerates*.

Sediments are usually deposited in horizontal layers. Changes in deposition rates may cause development of distinct planes called *bedding planes*, which separate sedimentary layers, or beds. Other changes in the processes of deposition may cause alternating beds of sand, limy mud, or clay to be formed. Because of such changing conditions, sedimentary deposits usually consist of mixtures of rock materials. Completely pure rocks, such as sandstones having no clay or lime, or limestones having no entrained mud or sand are rare. As a result, those deposits of sedimentary rock of high purity have often become extremely valuable for their unusual physical or chemical characteristics.

4. Metamorphism

Heat and fluids emanating from a magma may alter adjacent intruded rocks, creating a halo of *contact metamorphic rocks*. Rocks which become buried to depths of several miles or tens of miles are subjected to tremendous heat and pressure which, with the aid of contained or introduced fluids, cause their *metamorphism*. Original bedding may be destroyed and new layering imposed with the orientation of minerals in certain directions, so that the metamorphic rocks are *foliated*.

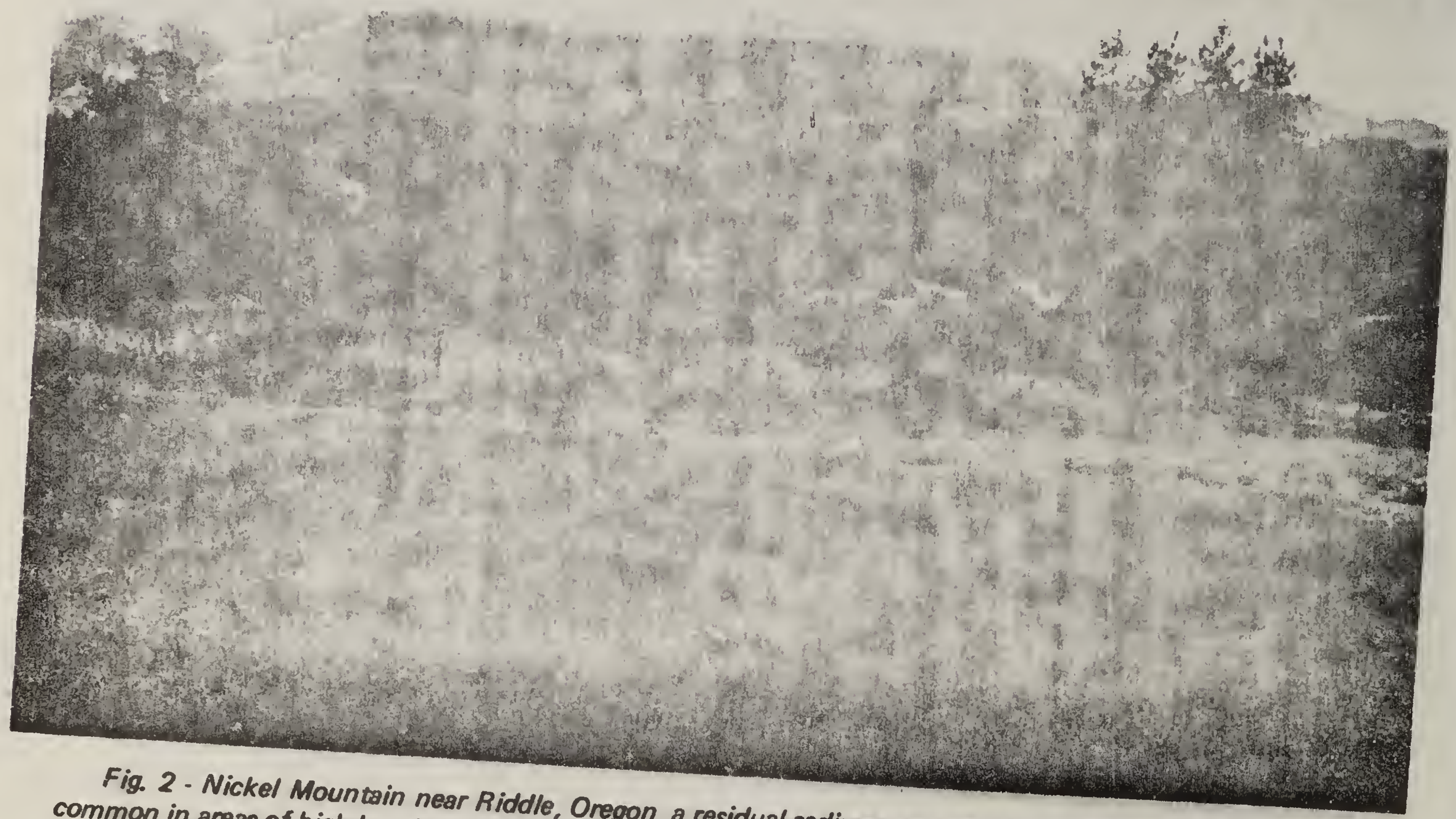


Fig. 2 - Nickel Mountain near Riddle, Oregon, a residual sedimentary deposit known as a laterite that is common in areas of high humidity and mountainous terrain.

5. Tectonic Processes

Different portions of the earth have, at different times, been uplifted above or depressed beneath the seas. Some of these movements have been broad and gentle, and have occurred on a regional or continental scale. More intense local and regional forces have crumpled layered rocks into *folds* having dimensions ranging from a few inches to several miles.

Rocks, like other materials, fracture when subjected to excessive stresses. Under certain conditions the resulting fractures have smooth, plane surfaces and are called *joints*. When movement occurs which offsets the rock on one side of a fracture from rock on the other side, the fracture is called a *fault*. Movement along faults may offset the rocks from less than one inch to more than several miles. Fault movements may be lateral, vertical, or diagonal combinations of both.

6. Mineral Deposition

Groundwater solutions, and solutions emanating from a cooling magma, may penetrate rocks along fractures and along tiny open spaces between mineral grains in the rock. Under certain conditions these solutions (which contain different chemical compounds) dissolve the rock-forming minerals, at the same time depositing other minerals in their place by precipitation from solution. This process of *replacement* of one group of minerals by another is the way in which many concentrated deposits of specific minerals are formed. The hot solutions given off by a cooling magma are water-bearing, and are called *hydrothermal* solutions or fluids. Surface or rainwater percolating through the earth is called *groundwater* or *meteoric water.*

Leaching, or the decomposition, dissolving, and removal of soluble minerals from rocks, may be caused by either hydrothermal or meteoric solutions. The dissolved mineral products may be dispersed or redeposited somewhere else as the same or different minerals, often in more concentrated form. If leaching and redeposition results in an increased concentration of a particular element or mineral, the deposit thus affected is considered to have been *enriched.*

Leaching and enrichment by meteoric waters have played an important part in the formation of many valuable mineral deposits. Gold, for example, is not as readily dissolved by meteoric solutions as are other associated minerals. The relative gold content of a mineral deposit may thus be increased through the leaching out and removal of originally associated minerals by groundwater, leaving an enriched residual gold deposit. Somewhat differently, portions of copper deposits in weathered zones may become enriched through the leaching of the copper content from surface rocks by groundwater and its redeposition at greater depths below the surface. In some instances, *secondary* deposits containing relatively high concentrations of native copper have been formed from original, or *primary*, deposits containing less than one percent copper.

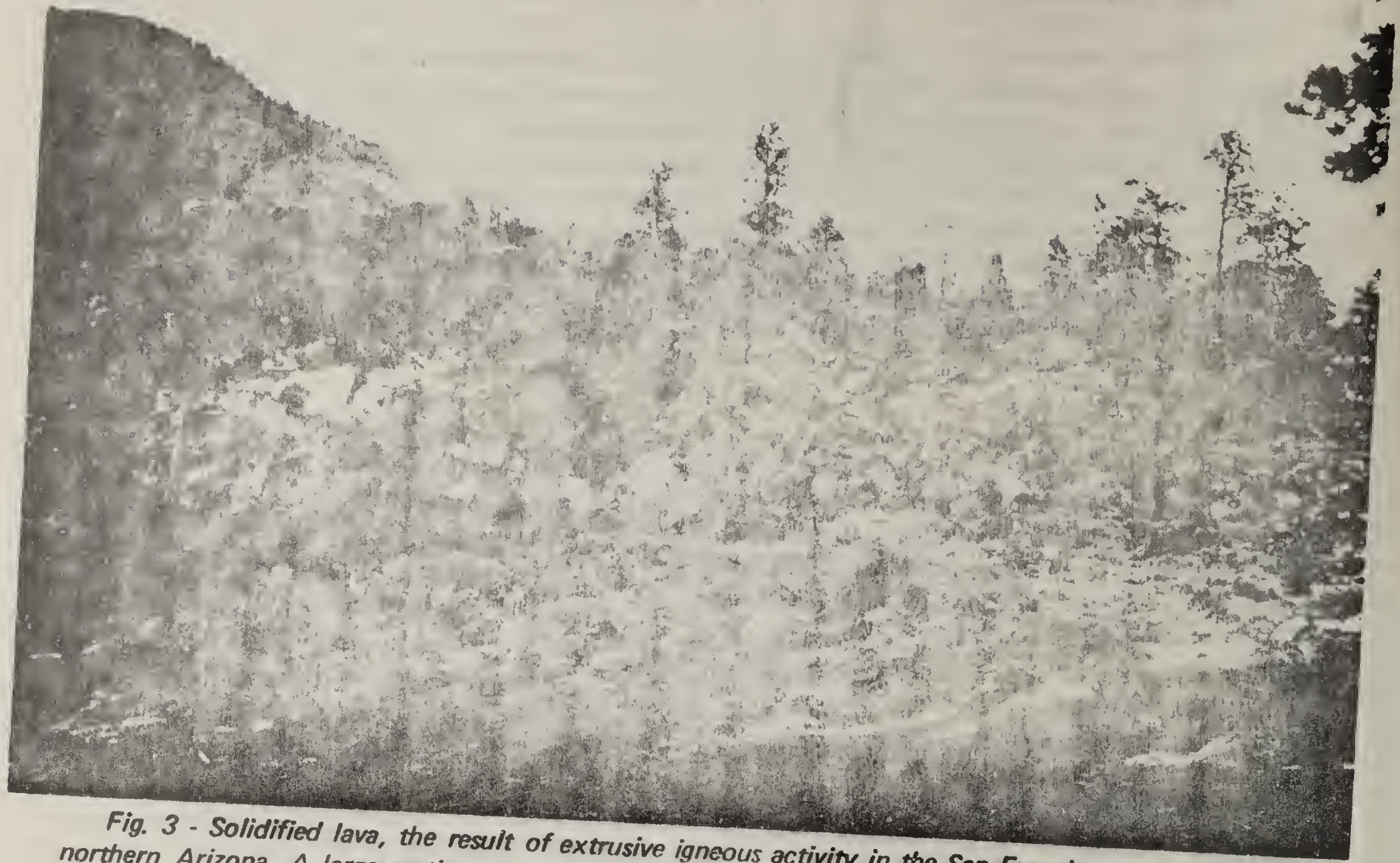


Fig. 3 - Solidified lava, the result of extrusive igneous activity in the San Francisco volcanic field of northern Arizona. A large section of eastern Oregon and Washington, as well as smaller areas in other western states, are covered with similar extrusive rock formations.

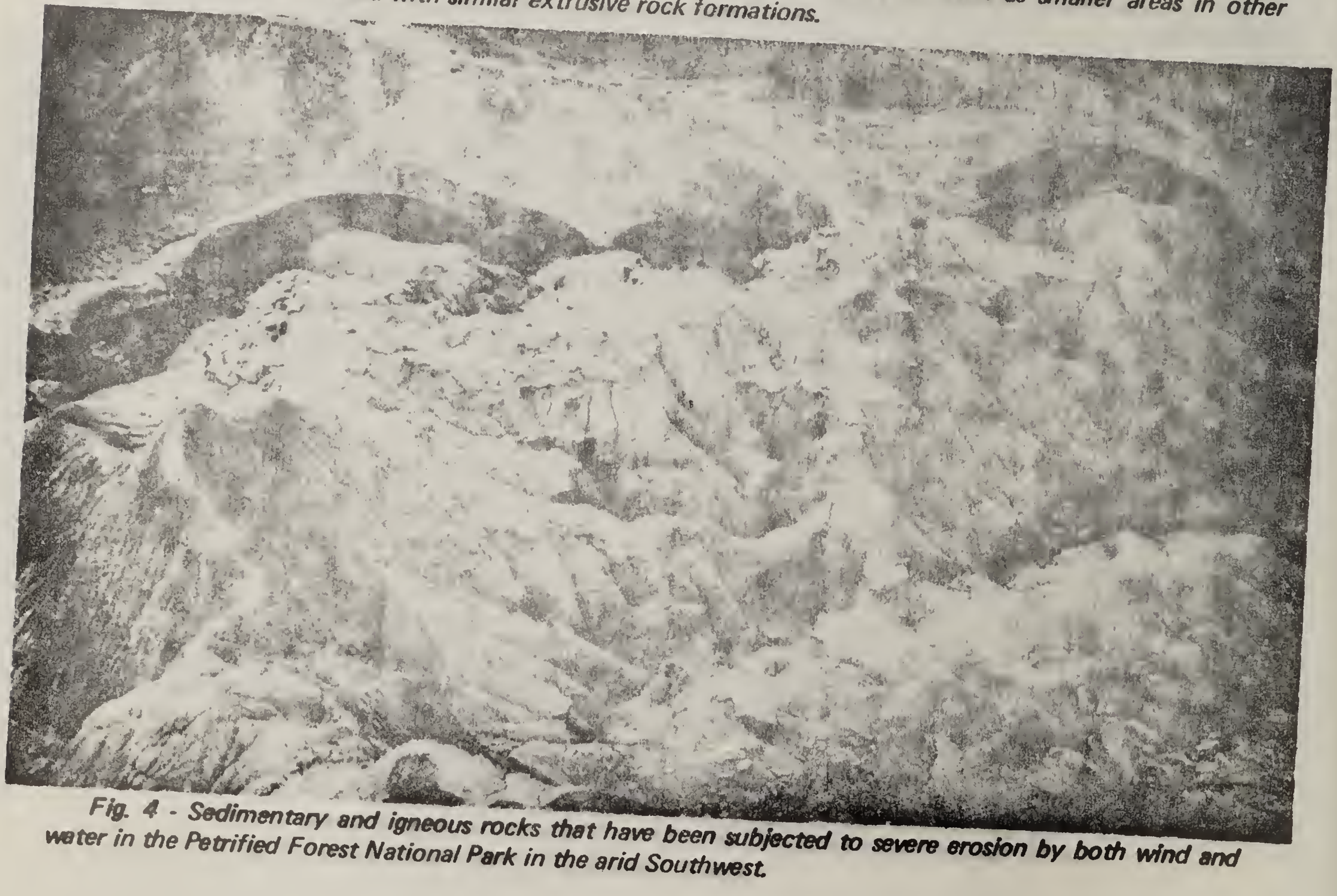


Fig. 4 - Sedimentary and igneous rocks that have been subjected to severe erosion by both wind and water in the Petrified Forest National Park in the arid Southwest.

D. THE STRUCTURES OF GEOLOGY

1. Igneous Structures

In general terms any *instrusive* igneous body of rock is a *pluton.* A *vein* or *lode* is only one of several types of structures frequently related to igneous activity. Intrusives covering a small area and having an irregular to cylindrical shape and which cut across the intruded rocks are called *stocks.* If such intrusions cover extremely large areas they are called *batholiths.* Some crosscutting plutons, gradually losing their force of penetration during the latter stages of intrusion, merely pushed the overlying rocks upward, rather than cutting through them, thus forming *domes. Dikes* are tabular intrusions which cut across the enclosing rocks. Intrusions which penetrate rocks parallel to their bedding or foliation are called *sills.* A *vein* itself is simply a relatively narrow or flat structure within a larger rock mass. A *lode* may be either a single vein or a system of related veins.

Extrusive structures are the result of volcanic activity. During such activity the extruded material (lava, ash, or cinders) may spread outward in flat layers, or *flows,* from a fissure or *vent.* Some of this material often piles up around the volcanic *crater* in the form of a *cone. Calderas* are enlarged craters formed through partial collapse of the caves or underlying rock, or through explosive activity which blows out a larger hole. The subterranean conduit supplying the magma for a volcano is called a *pipe.* Often volcanic activity is choked off when solidified magma, ash, and broken rock fragments fill the pipes, which are then called *plugs* or *necks.*

2. Sedimentary Structures

Horizontal and vertical movements of the earth's crust and igneous intrusions may crumple sedimentary rocks into *folds.* Downwarped beds form *synclines,* and upwarped beds form *anticlines.* Long, relatively narrow, and very large upwarps of the earth's crust are called *geanticlines.*

Rocks, particularly sedimentary beds, often sag downward as a loosely held blanket sags in the middle. Where the sag is large and drops below sea level adjacent to an ocean, the sea enters it. If the depression is large enough, most of a continent may be flooded and become the site of widespread deposition of sedimentary rocks. Instead of being broad, these sags have often taken the shape of long, narrow troughs in which extremely thick sediments are deposited. These are called *geosynclines,* just the converse of geanticlines. Smaller, more or less rounded downwarps in which deposition has taken place are called *basins.*

3. Tectonic Structures

If the forces exerted by the earth exceed the strength of a rock or its ability to bend into folds, the rock is fractured and segments on opposite sides of the fracture may be moved relative to each other. In cases where such movement occurs, the rock is said to be faulted. *Faults* may offset rock masses up, down, sideways, or diagonally. The displacement of rock formations along faults can be on the order of miles. Some faults extend tens of miles deep into the earth and extend hundreds of miles along the surface. Different faults range in attitude from nearly flat to vertical.

Rock caught between the opposing walls of a fault may be ground completely to rock flour or it may be broken and crushed into a mass of angular fragments called a *fault breccia.* Under some conditions large masses of rock may be shattered and *brecciated,* rather than faulted. Igneous intrusives often brecciate the rock along their margins and ahead of their paths of advance.

Formations of sedimentary rock are *never* uniform in thickness. Lower areas receive more sediments than more elevated ones, and at the margins of depositional areas the layers of sediments become thinner and pinch out. *Lenticular* formations or beds are discontinuous and have wide variations in thickness within relatively short distances. Although sedimentary beds are usually parallel to each other for any given sequence of deposition, shifting wind or water currents may have caused successive beds of sediments to be deposited at angles to each other. Then the *strata,* or layers, are *crossbedded.* Sand and gravel deposited in and on the margins of streams or rivers form *stream channel deposits,* which are discontinuous and often serpentine in form. Some sedimentary structures consist of a series of overlapping lenticular beds.

Sedimentary beds deposited on an erosion surface cut from older rock formations are said to unconformably overlie the older rocks. The formations on either side of this erosion surface, called an *unconformity,* may not be parallel to each other. Younger, flat-lying sedimentary beds often rest on tilted older beds, resulting in an unconformity that is angular.

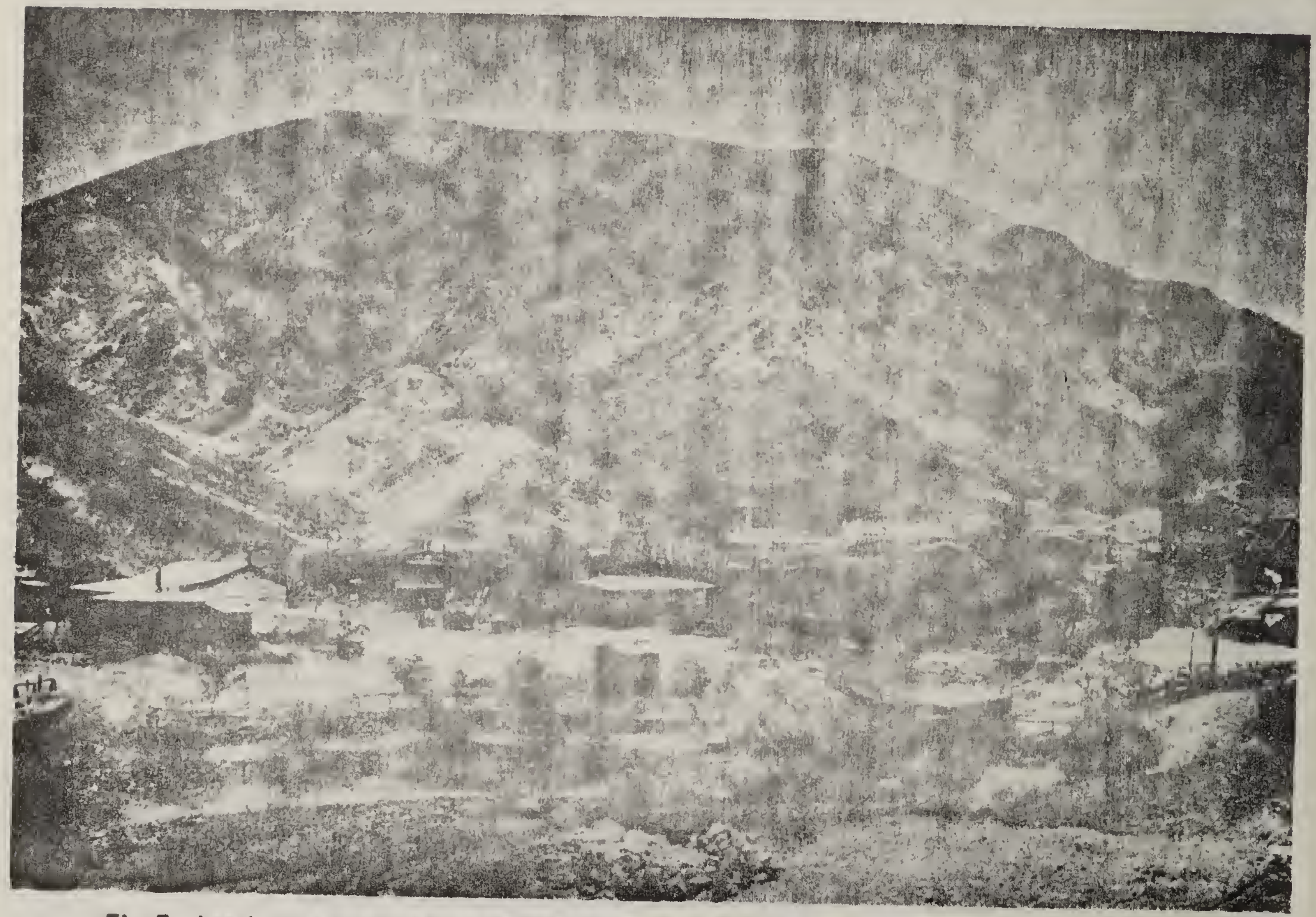


Fig. 5 - Leached cap rock rich in silica and iron oxides remaining after silver and other metallic sulfide minerals have been disolved; at Calico, near Barstow, in the Mohave Desert of Southern California. Such leached areas, called gossans, are commonly associated with metallic mineral deposits in arid and semi-arid regions and have frequently provided the surface indications of the presence of valuable mineral deposits at depth.

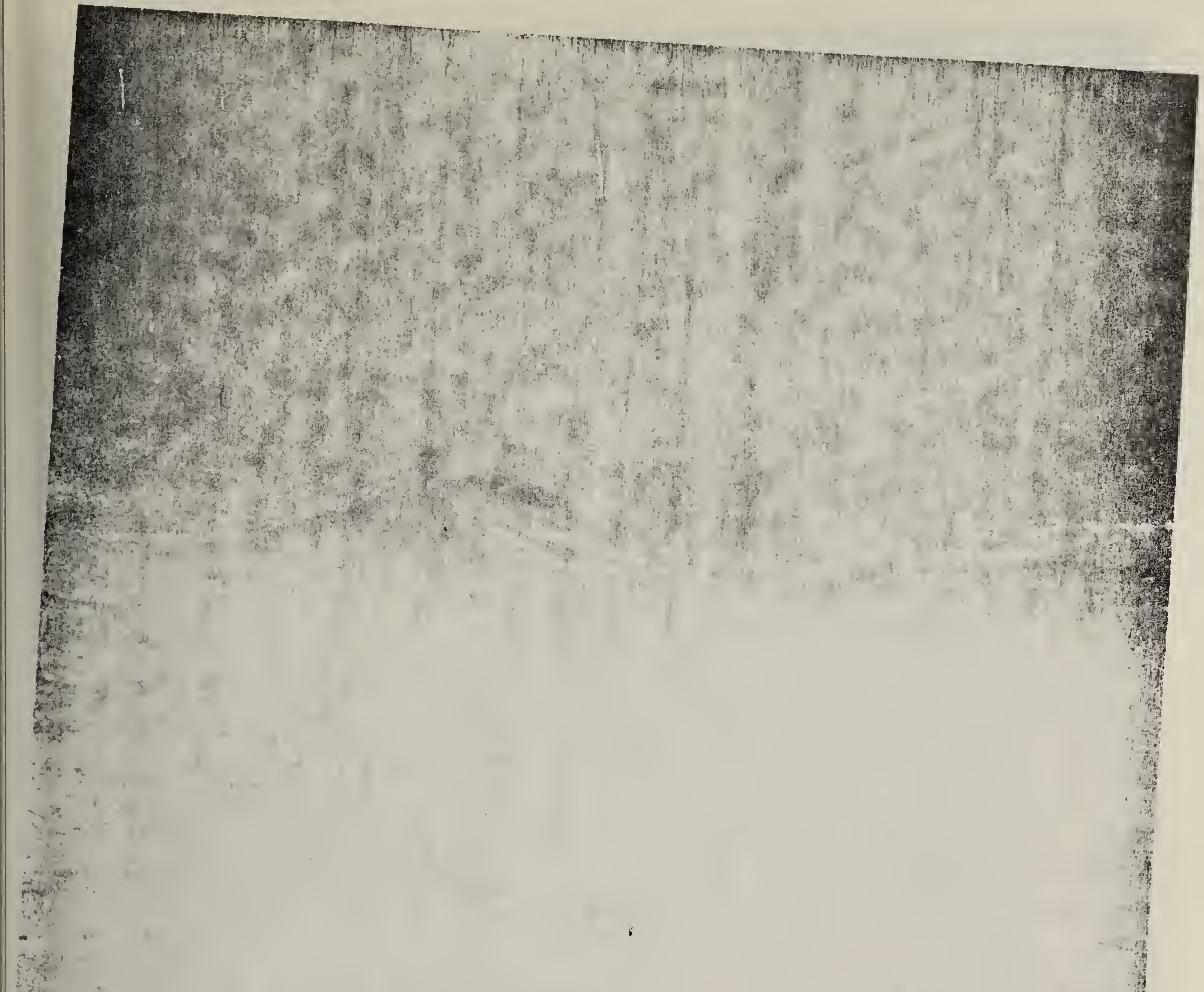


Fig. 6 - The eroded remnants of a volcanic plug and vertical dikes near Shiprock, New Mexico, where these intrusive structures penetrated the thick, horizontal, sedimentary rocks of the Colorado Plateau.

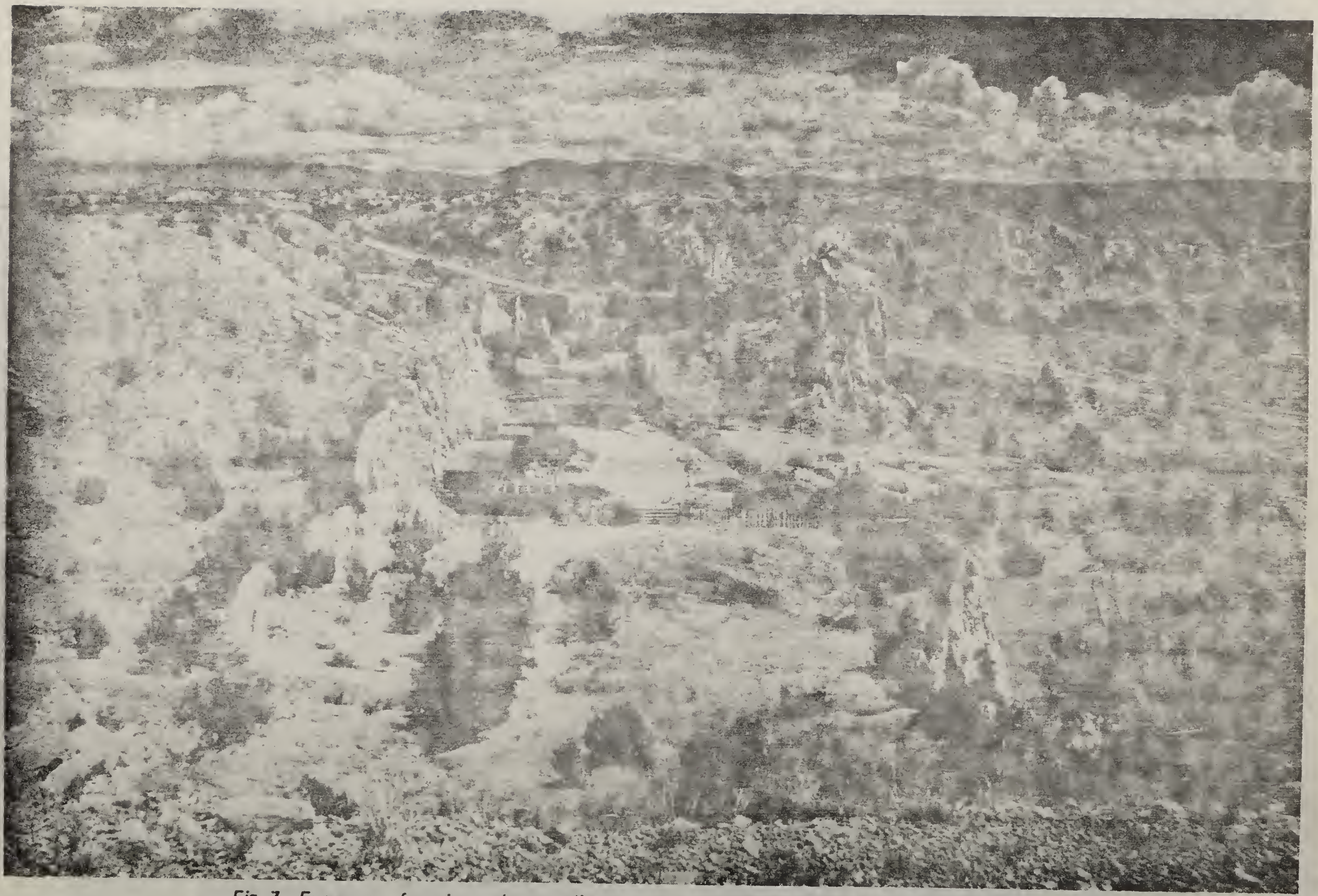


Fig. 7 - Exposures of erosion resistant sedimentary beds, mostly sandstone, that have been tilted to a nearly vertical position, in northern New Mexico. Extensive folding and tilting of sedimentary rocks that were originally horizontal is common in both the Mountain West and the Appalachian states.

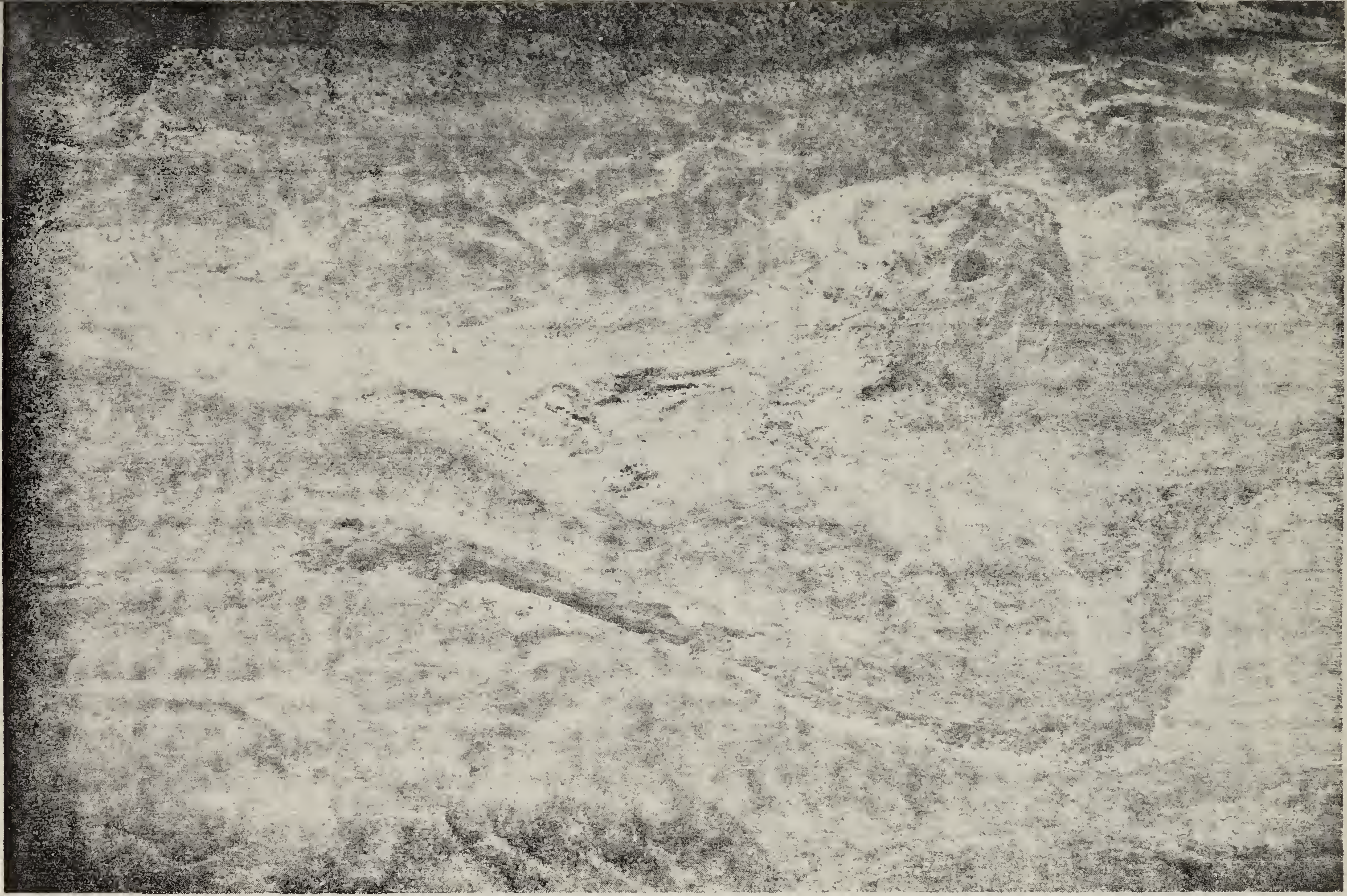


Fig. 8 · Exposed remnant of an ancient (Paleozic Age) stream channel, now turned to sandstone, subsequently covered by softer sediments of volcanic ash and unconsolidated clay in the Big Bend country of West Texas. Similar erratic and discontinuous formations on the Colorado Plateau have frequently contained relatively high concentrations of uranium minerals.

E. THE TIME OF GEOLOGY

Figure 10 shows the major geologic time subdivisions and the absolute time scale, as it is presently known. The names of many of the geologic time subdivisions are derived from rock types and the locations of rock groups characteristic of certain time intervals.

The history of the earth falls into distinct *eras*. The oldest era, the *Precambrian*, was by far the longest and is that about which we know the least. Except for the younger Precambrian, the rocks formed during this era resulted from enormous intrusive and extrusive igneous activity and have been affected by profound metamorphism. The existing rocks of this age are mainly schists, slates, altered lavas, and other products of metamorphism. This mixed-up mess is commonly called the *basement complex*, because it forms the basement upon which younger sedimentary rocks have been formed.

The more recent eras of geologic time, the *Paleozoic*, *Mesozoic*, and *Cenozoic* Eras, with their subdivisions, are partly defined by mountain-building *orogenies*, or *revolutions*, and partly by changes in the types of animal and plant life as evidenced by fossils contained in the rocks. In all instances, geologic time periods are arbitrarily defined and are by no means as accurately determined as written history.

Spasms of disturbance, resulting in folding, faulting, and usually extrusive igneous activity, are called *orogenies* or *revolutions*. Although affecting large areas in the United States, known geological revolutions have never been continental in scope. The *Appalachian Revolution* was confined to the eastern United States; the *Laramide Revolution* to the western portion.

Although the separation of geologic eras has normally been defined by orogenies, there was no widespread orogeny to mark the close of the *Precambrian* Era. As a result, the younger *Precambrian Beltian* series of quartzites (silicified sandstone) shown on geologic maps of the United States can hardly be distinguished, in places, from the overlying *Paleozoic* sediments. Such lack of sharp distinction is common in geology.

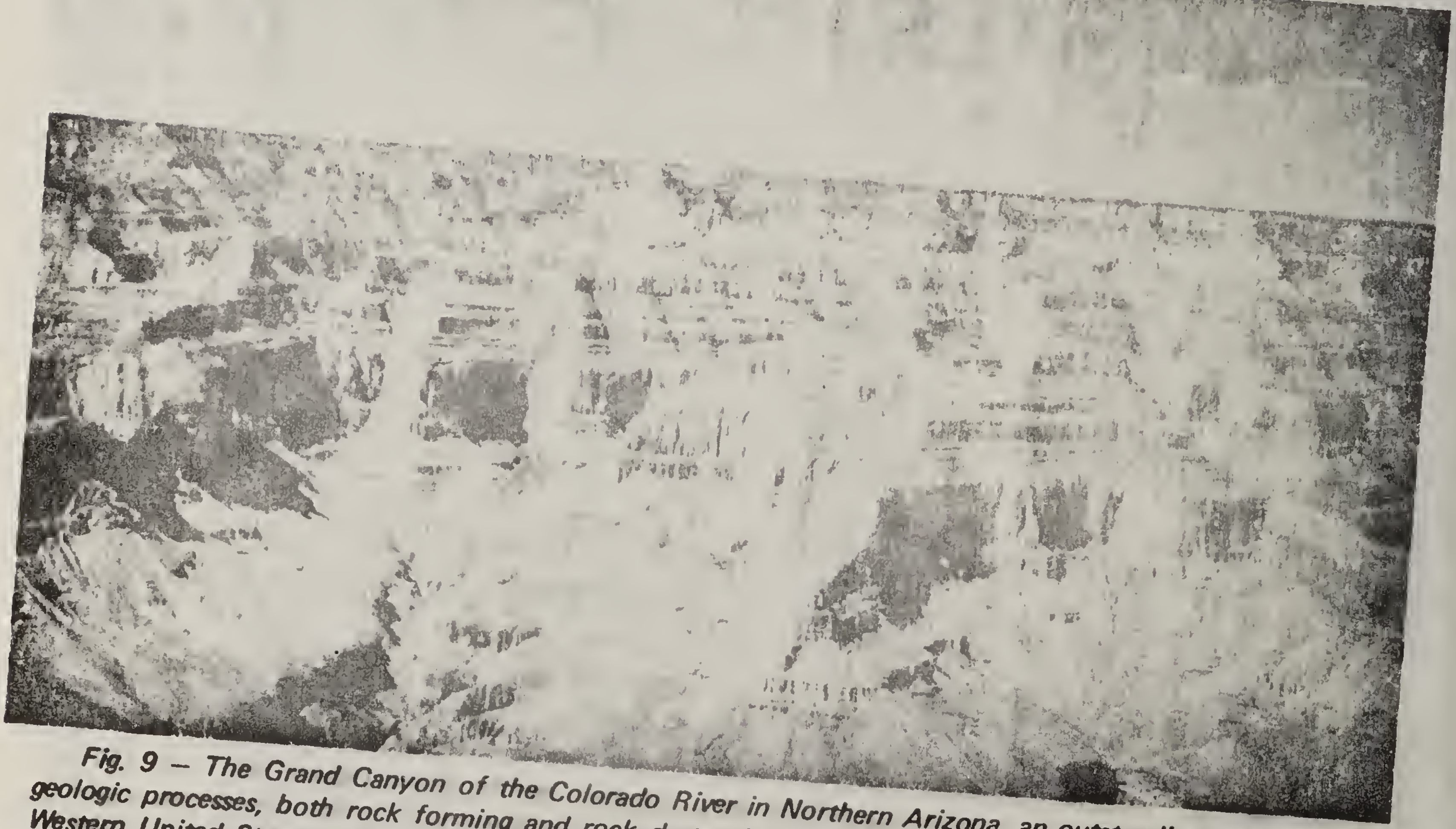
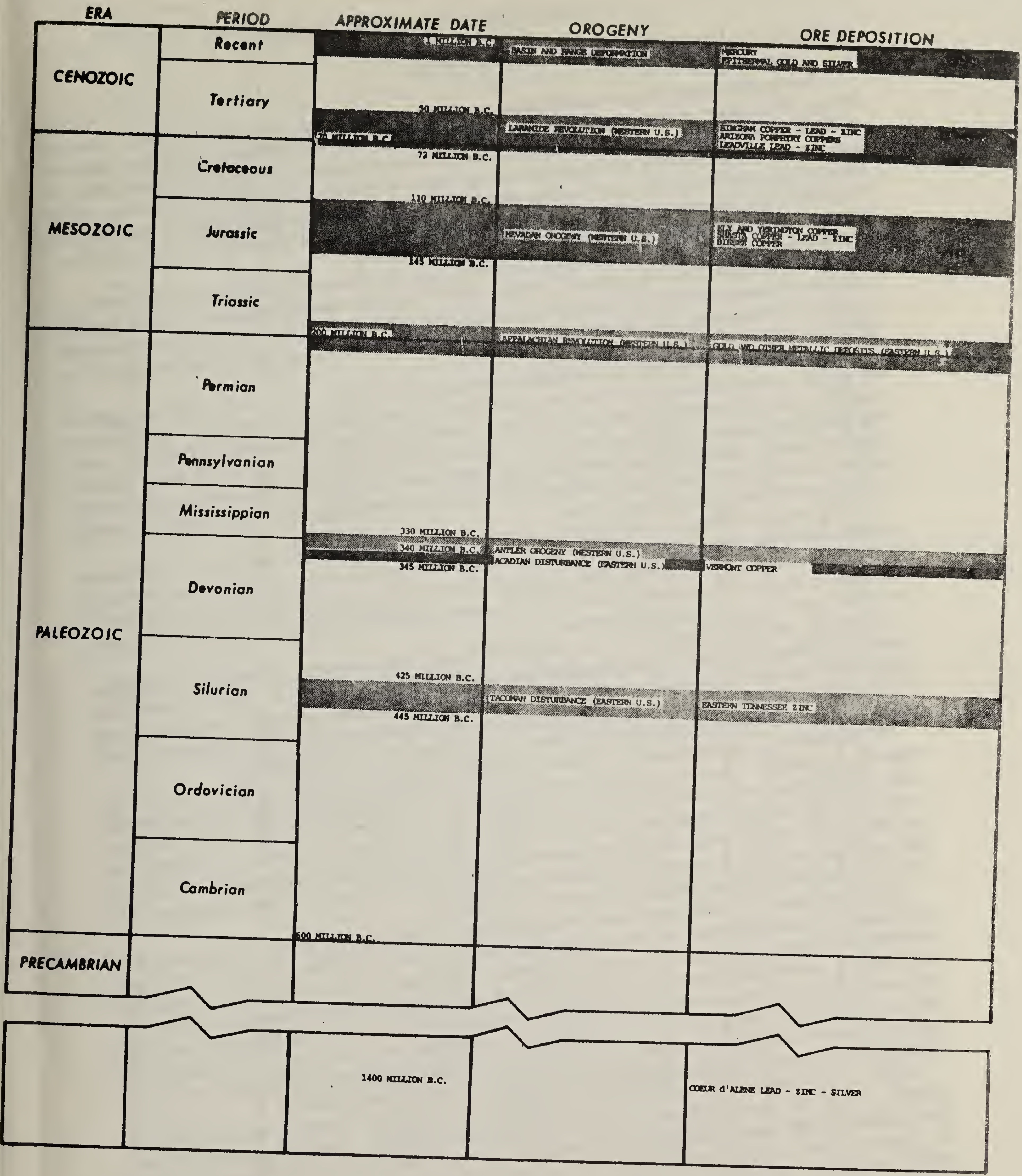


Fig. 9 – The Grand Canyon of the Colorado River in Northern Arizona, an outstanding example of geologic processes, both rock forming and rock destroying, and a record of the geologic history of the Western United States. Rocks of Paleozoic and Mesozoic age overlie the earlier Precambrian "basement complex" represented by the dark colored rocks at the bottom of the Canyon in the foreground.



ERA	PERIOD	APPROXIMATE DATE	OROGENY	ORE DEPOSITION
CENOZOIC	Recent	1 MILLION B.C.	BASIN AND RANGE DEFORMATION	MERCURY EPITHERMAL GOLD AND SILVER
	Tertiary	50 MILLION B.C.	LARAMIDE REVOLUTION (WESTERN U.S.)	BINGHAM COPPER - LEAD - ZINC ARIZONA PORPHYRY COPPERS LEADVILLE LEAD - ZINC
MESOZOIC		70 MILLION B.C.		
	Cretaceous	72 MILLION B.C. 110 MILLION B.C.		
	Jurassic	145 MILLION B.C.	NEVADAN OROGENY (WESTERN U.S.)	ELY AND YERINGTON COPPER SHASTA COPPER - LEAD - ZINC BISBEE COPPER
	Triassic			
PALEOZOIC	Permian	200 MILLION B.C.	APPALACHIAN REVOLUTION (EASTERN U.S.)	GOLD AND OTHER METALLIC DEPOSITS (EASTERN U.S.)
	Pennsylvanian			
	Mississippian			
	Devonian	330 MILLION B.C. 340 MILLION B.C. 345 MILLION B.C.	ANTLER OROGENY (WESTERN U.S.) ACADIAN DISTURBANCE (EASTERN U.S.)	VERMONT COPPER
	Silurian	425 MILLION B.C. 445 MILLION B.C.	TACONIAN DISTURBANCE (EASTERN U.S.)	EASTERN TENNESSEE ZINC
	Ordovician			
	Cambrian	600 MILLION B.C.		
PRECAMBRIAN				
		1400 MILLION B.C.		COEUR d'ALENE LEAD - ZINC - SILVER

Fig. 10 - Geologic time on the North American continent. The vertical scale is roughly proportional to the elapsed time involved in the specific eras, periods, and orogenies.

F. THE ECONOMICS OF GEOLOGY

1. The Components of Economic Mineral Deposits

The earth's crust is not a homogeneous mass and although every element may have an average frequency of occurrence in that mass, in very few specific areas does any element exist in exactly that average concentration. In some places particular elements may be completely absent, while in others they may exist in amounts far above the average. Since the earth's crust is made up of rocks, which in turn are made up of minerals, it may be said that the earth's crust is one gigantic series of adjacent mineral deposits. At any one time, some of these will be more or less valuable than the others.

Deposits of certain minerals may be valuable to man because of the specific elements or minerals contained in the deposits, while others may be valuable because of the specific physical or chemical characteristics of the rock itself. Where a rock mass exists that contains a mineral commodity that is useful to man in greater than average concentration, it may be termed a *deposit of a valuable mineral.*

Most elements that are of economic importance to man occur extensively throughout the earth's crust and are found in many different types of rocks. Aluminum and iron, for example, are undoubtedly two of the most useful elements in modern civilization, and together they make up approximately 13 percent of all the material in the earth's crust. Only in certain limited areas, however, do they occur in sufficient quantities and in the proper chemical combinations to allow them to be commercially extracted from the earth for the use of man at the present time.

As shown in Table 1, most of the useful elements are much scarcer than are aluminum or iron, but like them, they must (under current technical and economic conditions) be found in a relatively concentrated state and in a specific chemical form in order to be utilized by man. Such concentrations of the proper chemical compounds in the earth's crust we refer to as *valuable mineral deposits.*

Whether or not a deposit of a valuable mineral is or is likely to become a valuable mineral deposit depends upon engineering and economic factors as well as geological conditions. In general terms, a *valuable* (or potentially valuable) *mineral deposit* contains some commodity (a rock or a mineral) which can be, or has the potential of being, removed from the earth and marketed, either before or after some form of processing.

Under existing technological conditions, certain minerals are more valuable than others because a particular element (usually a metal) can be readily prepared from them or because they themselves form a useful chemical compound, or because they have useful physical properties. It has been traditional to classify such useful minerals according to whether or not they were chiefly valuable as the source of a metal or for other purposes. Such methods of classification have normally considered minerals to be in one of three categories: (1) metallic minerals; (2) non-metallic minerals; or (3) fuels.

With the advent of nuclear energy, however, and continuing advances in chemistry and metallurgy, these categories are not as clear-cut as they once were thought to be. The prime example, of course, is uranium, which is at once a metal and a fuel. Uranium minerals are thus both a source of a metal and fuel. There are other examples, particularly of minerals such as sodium chloride or rock salt which are valuable both as a source of metal (sodium) and as a chemical compound, thus being both a metallic mineral and a non-metallic or industrial mineral at the same time. An even more important example is bauxite, an ore of aluminum and an industrial mineral used in refractories and as an abrasive.

Table 2 provides a list of mineral commodities classified according to a traditional system. Some of the problems in such classification may be readily apparent in the overlapping of classes and the extreme heterogeneity within the industrial minerals category. In many respects, such classifications are geologically irrelevant, as is shown in Table 3 which classifies the most significant economic minerals according to the geologic environments in which they commonly occur. Under this method of classification, the

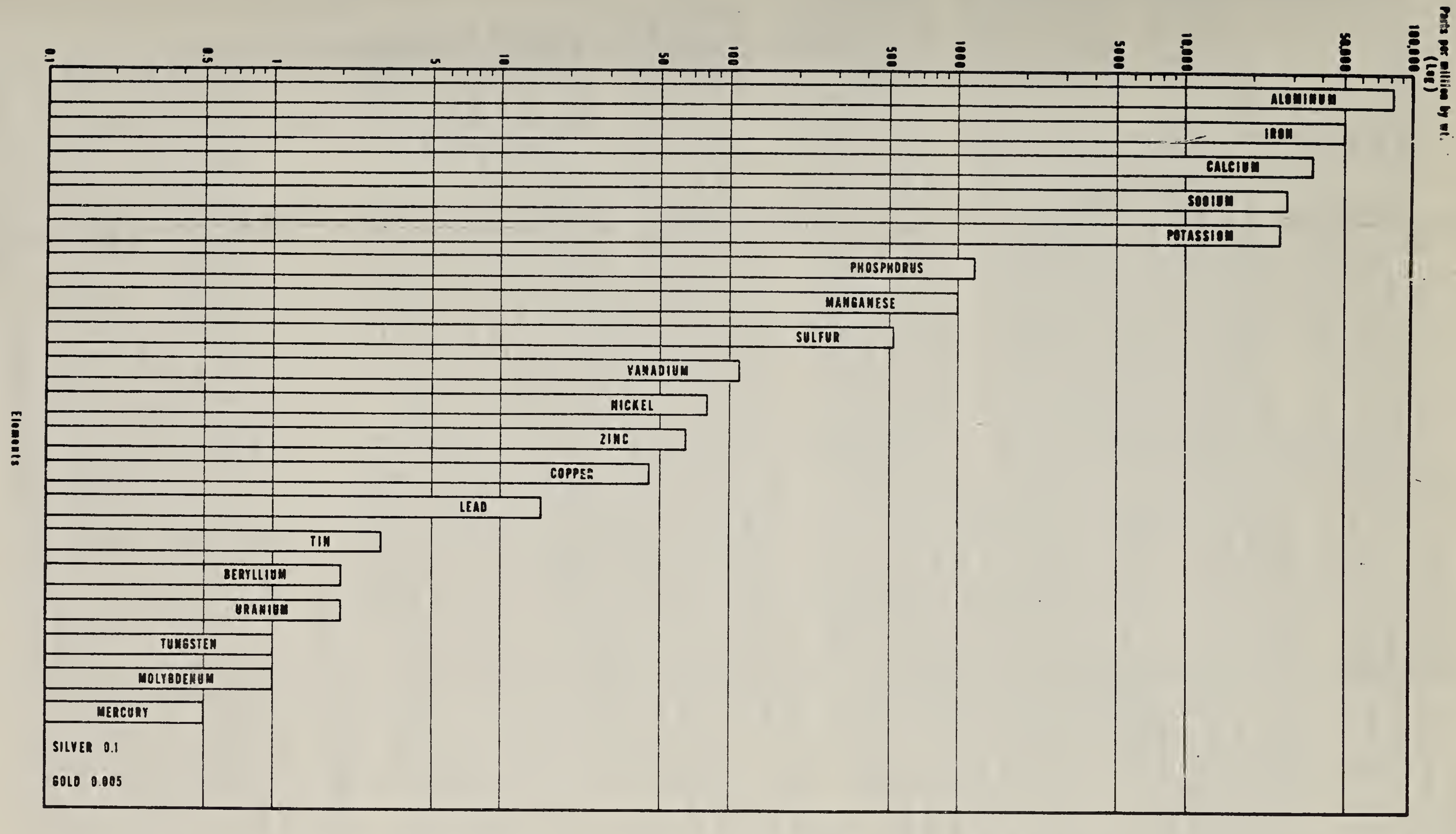


Fig. 11 - The average concentration of various elements in the earth's crust. Although many elements occur widely and in many types of rocks, they do not occur in sufficient quantities nor in chemically appropriate form for commercial utilization under existing technological and economic conditions.

overlapping is even more apparent. *Any system of classifying minerals which proposes mutually exclusive categories is contrary to geological reality.* Even classification on the basis of chemical composition, involving separation on the basis of the dominant element, is impossible, because minerals are not all fixed chemical compounds. Many have variable chemical compositions in which one element may substitute for another within a given range.

For most metallic mineral deposits (i.e., deposits of minerals normally valuable for their metallic content), the distinction between a *deposit of a valuable mineral* and a *valuable mineral deposit* has involved the use of the terms, *ore* and *ore minerals*. *Ore minerals* are those minerals from which metals are commonly extracted and the most important ones are listed in Table 4.

A deposit of *ore minerals* in geological terms, however, is not always an *ore deposit* in mining terms. While an *ore mineral* is a mineral from which a metal can be feasibly extracted, an *ore deposit* (or an *ore body*) is a mass of *rock* from which a metal can be profitably produced. Although originally confined to metals production, the term *ore* has been applied to any mass of rock (i.e., any mineral deposit) from which a valuable mineral commodity may be extracted at a profit. What is or is not *ore* thus becomes dependent upon economic as well as geological criteria.

Within a given mineral deposit, *ore minerals* are normally associated with other minerals which, under the particular circumstances, are not valuable by themselves. These less valuable minerals are termed *gangue*. One of the most common gangue minerals is silica, and others are listed in Table 5. It should be noted that while they may be relatively valueless when in the presence of ore minerals, many of the common gangue minerals are themselves important as industrial minerals and are often of considerable value in the proper circumstances.

Just as *gangue minerals* are the antithesis of *ore minerals*, so *waste* is the antithesis of *ore*. In a given rock mass, that rock which does not contain valuable minerals, or which contains too little a concentration of them to be economically valuable as a source of those minerals, is called *waste*. Waste, like ore, is thus also an economic rather than a geologic term, and changing engineering and economic conditions may change a given mass of ore and gangue minerals from waste to ore and back again many times.

Both ore and waste are important features of a mineral deposit. In a simple vein deposit, for example, the amount of metal in a ton of rock determines the nominal value of that ton, but the ratio of ore minerals to gangue minerals and the width of the vein determine whether the rock is ore or waste. If the vein is too narrow, the amount of waste rock on either side of the vein which has to be mined to allow room in which to work may be so high that the overall value per ton of rock mined is too low to make ore. The grade of the ore and the width of the vein may vary within narrow limits for hundreds of feet in some veins while in others, alternate pinching and swelling of the veins and an irregular distribution of the ore minerals may result in a series of ore bodies, termed *ore shoots*, which are flanked by low-grade or waste vein material.

2. The Processes of Mineral Deposition

Primary mineral deposits may be created as a result of the rock-forming processes such as extrusion, intrusion, or sedimentation. Or they may be created by the introduction into existing rocks of hydrothermal fluids containing elements and compounds which crystallize upon cooling as minerals. During the cooling and crystallization of some igneous rocks, specific minerals may be trapped in these rocks as widely disseminated grains, or they may be more or less segregated and concentrated within the rocks as zones or bands. Some iron, copper, nickel, platinum, and chromium mineral deposits were formed in this way. Acidic extrusive igneous rocks which are rich in water may be cooled so rapidly that they chill to a glass, as perlite, rather than crystallizing.

Primary mineral deposits frequently result from sedimentation and metamorphism. Beds

Table 1

AVERAGE OCCURRENCE OF SELECTED ELEMENTS IN THE ROCKS OF THE EARTH'S CRUST

Elements	Average Concentration in the Earth's Crust (in parts per million by weight)	Average Concentrations Normally Needed for Economic Mineral Resource Utilization in 1968 (in parts per million by weight)
Aluminum	81,300	265,000 to 290,000 (in oxide form)
Iron	50,000	300,000 (in oxide form)
Calcium	36,300	209,000 (in hydrated sulfate form) 380,000 (in carbonate form)
Sodium	28,300	390,000 (in chloride form) 220,000 (in carbonate form)
Potassium	25,900	150,000 (in solid oxide form) 21,000 (in oxide form in brine)
Phosphorus	1,180	65,000 to 160,000 (in phosphate form)
Manganese	1,000	350,000
Sulfur	520	200,000 to 400,000
Vanadium	110	10,000
Nickel	80	14,000
Zinc	65	35,000 to 90,000
Copper	45	7,000
Lead	15	9,000 to 60,000
Beryllium	2	40,000 (in silicate form)
Uranium	2	800 (in oxide form)
Tungsten	1	4,000 (in oxide form)
Molybdenum	1	3,000
Mercury	0.5	2,000
Silver	0.1	400
Gold	0.005	15

Sources of Data: Brian Mason: *Principles of Geochemistry*, New York: John Wiley & Sons; 1958, and various others.

and lenses of limestone, potash, diatomite, phosphate, and sodium carbonate (trona) are the results of sedimentary rock-forming processes. The high pressures and temperatures involved in metamorphism convert shale to slate and organic matter to graphite. Garnet is another product of metamorphism.

Primary mineral deposits formed through the introduction of hydrothermal fluids may occur as fillings in previously open spaces, along fractures in the rocks, as replacements of the rock original minerals in the adjacent fractures and faults. Many deposits of base and precious metals and uranium were formed in this way.

Secondary mineral deposits are formed by the action of geologic processes on primary mineral deposits. Weathering and erosion, for example, cause the formation of bauxite (aluminum ore) deposits by residual concentration after weathering has broken down aluminum bearing rocks and subequent erosion has removed the non-aluminum bearing minerals. Placer gold deposits are also secondary in nature. Gold-bearing rock fragments are broken down as they are moved downslope and transported in streams and rivers. The gold, usually in finely divided particles, becomes separated from the rock and, because it is heavier, sinks to the bottom of the stream. Placer deposits are usually formed where the water currents decrease in velocity, permitting the heavier material being transported to come to rest.

Other secondary mineral deposits are created by the chemical leaching of primary mineral deposits by groundwater. This action results in the lateral and downward transportation of copper, lead, zinc, silver, and uranium compounds in solution. Redeposition from solution below the water table forms secondary deposits of these metals. Gold is also concentrated residually by the leaching out of associated *gangue* minerals in near-surface zones of weathering.

3. The Structures of Mineral Deposition

Many mineral deposits formed as the result of sedimentary processes occur as generally flat-lying lenses or beds which may extend for thousands of feet or tens of miles in horizontal directions but are rarely more than a few hundred feet thick. These deposits occur in sedimentary basins, along ancient slopes or stream channels, and in ancient lagoons.

Later structural deformation may alter the form and attitude of some of these deposits. Salt domes along the coast of the Gulf of Mexico resulted from the squeezing of salt from flat-lying beds upward along zones of weakness. The phosphate deposits of the Western United States have been extensively tilted, folded, and faulted subsequent to their deposition. In the Eastern United States, many limestone beds have been tilted to an almost vertical position.

Lenticular masses, veins, and zones of disseminated minerals are characteristic forms of mineral deposits resulting from the processes of metamorphism. These deposits may conform to the attitudes of the enclosing rocks (slate, for example) or they may be crosscutting (as in some pegmatite deposits). Garnet in upper New York state occurs as scattered (disseminated) crystals and rounded grains in metamorphic rock. Some of the garnet occurs in rounded masses larger than watermelons. The dimensions of ore bodies formed through metamophism are usually in the range of hundreds to several thousands of feet.

Veins consist of aggregates of minerals which have been deposited in fractures and faults, or have replaced the rock immediately adjacent to the fractures. The veins are rudely tabular, but usually thicken and thin at irregular intervals. *Quartz* (silicon dioxide), *calcite* (calcium carbonate), and *pyrite* (iron disulfide) are common *gangue* minerals in many metallic vein deposits. Many base and precious metals, uranium, talc, and asbestos deposits occur as lens-like masses along faults or in veins, and may have attitude from horizontal to vertical. The lengths and widths of the deposits of these mineral commodities are usually in the order of hundreds to thousands of feet, while their thicknesses vary from less than a foot to more than one hundred feet. Some of the largest vein deposits have been followed

Table 2

GROUPING OF MINERALS ACCORDING TO ESTABLISHED CLASSIFICATION SYSTEMS

A. Industrial Classification of Metals

1. Ferrous Metals

Iron

2. Ferro-alloy Metals
(sometimes included in the
ferrous classification)

Manganese
Chromium
Nickel
Molybdenum
Cobalt
Tungsten
Vanadium
Columbium

3. Light Metals

Aluminum
Magnesium
Titanium
Zirconium

4. Non-Ferrous Base Metals

Copper
Lead
Zinc
Tin
Antimony
Cadium
Bismuth

5. Nuclear Elements

Uranium
Thorium
*Beryllium

6. Precious Metals

Gold
Silver
Platinum

B. Non-Metallic Minerals (also termed industrial minerals and rocks)

Potash
Sodium Carbonate (Trona)
Sodium Sulfate
Salt
Borax and Borates
Gypsum
Lithium minerals
Strontium minerals
Barite
Phosphate
Flourite
Limestone
Dolomite
Magnesite
Chalk
Diatomite
Clay
Sandstone, Quartzite
Shale
Bentonite
Perlite
Graphite
Mica
Asbestos
Talc and Soapstone
Vermiculite
Pyrophyllite
Slate
Sillimanite Group (topaz, kyanite, andalusite, sillimanite, dumortierite)
Garnet
Crushed Stone
Sand and Gravel
Dimension Stone
Sulfur
Diamonds
Bauxite

*Beryllium is also a common ferrous and non-ferrous alloying metal.

Table 3

CLASSIFICATION ACCORDING TO COMMON ENVIRONMENT OF OCCURRENCE

1. **Association with igneous intrusions**

   Iron
   Ferro-alloy metals
   Non-ferrous base metals (copper, lead, zinc, tin)
   Precious metals (gold, silver)
   Nuclear elements
   Titanium
   Magnesite
   Barite

2. **Association with sedimentary rocks–concentration by weathering and/or precipitation as sedimentary deposits**

   Iron (in oxides)
   Manganese (manganese oxides)
   Aluminum (bauxite)
   Uranium
   Vanadium
   Copper
   Nickel

3. **Extraction from sea water**

   Magnesium
   Salt

4. **Beach and stream placer deposits–beaches, streams, rivers**

   Monazite (rare earths, thorium)
   Titanium minerals (rutile, ilmenite)
   Tin (cassiterite)
   Gold
   Mercury
   Zirconium (Zircon)
   Silica sand (high-purity quartz sand deposits)

5. **Pegmatite deposits**

   Feldspar
   Quartz
   Rare-earth minerals (Columbium, tantalum, hafnium)
   Lithium minerals
   Beryllium

Table 3 (continued)

6. **Evaporite deposits**

   Potash
   Sodium Carbonate
   Sodium Sulfate
   Salt
   Borax and Borates
   Gypsum
   Lithium minerals

7. **Chemically precipitated sedimentary rocks**

   Sulfur
   Phosphate
   Strontium minerals
   Barite
   Limestone
   Dolomite
   Magnesite
   Chalk

8. **Other sedimentary rocks**

   Diatomite
   Clay
   Shale
   Sandstone, Quartzite
   (silica sand)

9. **Volcanic rocks**

   Bentonite
   Perlite

10. **Metamorphic rocks**

    Graphite
    Mica
    Asbestos
    Talc, Soapstone
    Vermiculite
    Pyrophyllite
    Slate
    Sillimanite group (Topaz, Kranite, Andalusite, Sillimanite, Damarticrite)
    Garnet (abrasive)
    Magnesite
    Diamond

11. **From sedimentary, igneous, and metamorphic rocks**

    Crushed Stone
    Dimension Stone
    Sand and Gravel

and mined for several miles in a horizontal direction as well as to several thousands of feet in depth.

Replacement deposits may be disseminated or massive. Many of the large copper deposits of the world consist of disseminated grains and veinlets of copper and iron sulfides which have replaced the primary rock minerals and filled small fractures in the host rock. The largest lead deposits in the United States are bedding replacement deposits of lead sulfides in carbonate rocks. These ore bodies, both disseminated and massive (i.e., bodies in which the ore is more or less continuous with little gangue or country rock separating the valuable minerals), were formed by the selective replacement of calcium carbonate from certain limestone beds in shattered and faulted zones. Some replacement deposits of copper, lead, and zinc occur in contact metamorphic zones adjacent to igneous intrusions, and may be quite irregular in shape and highly variable in size. Massive sulfide replacement deposits of copper, lead, and zinc may have cigar-to-football-shaped forms with dimensions of less than a hundred to more than a thousand feet.

Disseminated copper deposits usually have an area of less than one to two square miles and may extend three hundred to a thousand feet or more in depth. *Bedded replacement* lead, zinc, or copper deposits in limestone occur generally in more or less flat-lying clusters having lateral dimensions of a hundred to several thousand feet but are usually less than a hundred feet thick.

Deposits formed by residual concentration (bauxite and nickel laterites) have more or less flat-lying tabular forms of larger lateral dimensions (several thousand feet to several miles) with thicknesses of a few hundred feet. Placer deposits are usually not more than a few tens of feet thick, with valuable minerals occurring in relatively narrow and relatively long, horizontal patterns. These deposits are flat-lying and have sinuous outlines if they were deposited in streams or rivers. If deposited along beaches, they may be roughly rectangular in outline.

4. The Age of Mineral Deposits

Most metalliferous mineral deposits, and other mineral deposits resulting from metamorphic processes, were formed during periods of major geologic disturbances, or revolutions. These revolutions were characterized by episodes of folding, faulting, igneous intrusion and extrusion, and metamorphism. Such major geologic disturbances have taken place in different parts of the United States at different times. Large portions of the interior of the United States have remained relatively undisturbed since Precambrian time. By contrast, the Pacific Coast region has been the site of repeated geologic disturbances and has a complex history of deformation. The Appalachian Region has also undergone extensive disturbance, but not as recently as in the West.

The bulk of known metallic mineralization in the United States apparently occurred during four major periods of geologic time: Precambrian, Triassic - Jurassic, Laramide (late Cretaceous - early Tertiary), and middle to late Tertiary. (See Figure 10.) Most of the base and precious metal deposits in the Western United States were formed during the Laramide Revolution and Tertiary time. The environments of deposition, the types and relative abundance of source materials, and subsequent geologic events, all controlled the types of deposits formed and their characteristics. As the environments, deposition, and source materials varied throughout geologic time, different types of mineral deposits formed at different places and at different depths. During the Permian period, for example, an arid environment caused the formation of saline deposits, including potash, in shallow lagoons along what is now the New Mexico-Texas border. At the same time sandstone, shale, and limestone were deposited in adjoining areas, volcanoes were active in California, and the Appalachian Region was undergoing folding and faulting, creating other types of mineral deposits.

Subsequent geologic events have destroyed some existing mineral deposits and enhanced the value of others. For example, portions of some gypsum deposits in southern Arizona were later converted to relatively useless anhydrite as a result of local geologic disturbances. On the other hand, deposits of volcanic ash formed in what is now Wyoming during Tertiary time were altered by the leaching action of surface water and converted to now valuable deposits of bentonite clay. Other examples are legion.

Fig. 12 - Tilted sedimentary beds in Northeastern Utah in the Western Phosphate Field that includes parts of Utah, Idaho, Wyoming, and Montana. Broad folding and subsequent enrichment by weathering and erosion of sediments containing greater than average concentrations of phosphorus have produced economically valuable industrial minerals deposits throughout a wide area. In the center of the above photograph is a phosphate mining operation and plant owned by the Stauffer Chemical Company.

Table 4

COMMON ORE MINERALS

Metal	Ore Mineral	Composition	Percent Metal
Gold	Native gold	Au	100
	Calaverite	$AuTe_2$	39
	Sylvanite	$(Au,Ag)Te_2$	
Silver	Native Silver	Ag	100
	Argentite	Ag_2S	87
	Cerargyrite	AgC_1	75
Iron	Magnetite	$FeO \cdot Fe_2O_3$	72
	Hematite	Fe_2O_3	70
	Limonite	$Fe_2O_3 \cdot H_2O$	60
	Siderite	$FeCO_3$	48
Copper	Native copper	Cu	100
	Bornite	Cu_5FeS_4	63
	Brochantite	$CuSO_4 \cdot 3Cu(OH)_2$	62
	Chalcocite	Cu_2S	80
	Cholcopyrite	$CuFeS_2$	34
	Covellite	CuS	66
	Cuprite	Cu_2O	89
	Enargite	$3Cu_2S \cdot As_2S_5$	48
	Malachite	$CuCO_3 \cdot Cu(OH)_2$	57
	Azurite	$2CuCO_3 \cdot 2H_2O$	55
	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	36
Lead	Galena	Pbs	86
	Cerussite	$PbCO_3$	77
	Anglesite	$PbSO_4$	68
Zinc	Sphalerite	ZnS	67
	Smithsonite	$ZnCO_3$	52
	Calamine	$H_2Zn_2SiO_5$	54
	Zincite	ZnO	80
Tin	Cassiterite	SnO_2	78
	Stannite	$Cu_2S \cdot FeS \cdot SnS_2$	27
Nickel	Pentlandite	$(Fe,Ni)S$	22
	Garnierite	$H_2(Ni,Mg)SiO_3 \cdot H_2O$	

Table 4 (Continued)

Metal	Ore Mineral	Composition	Percent Metal
Chromium	Chromite	$FeO{\cdot}Cr_2O_3$	68
Manganese	Pyrolusite	MnO_2	63
	Psilomelane	$Mn_2O_3{\cdot}xH_2O$	45
	Braunite	$3Mn_2O_3{\cdot}MnSiO_3$	69
	Manganite	$Mn_2O_3{\cdot}H_2O$	62
Aluminum	Bauxite	$Al_2O_3{\cdot}2H_2O$	39
Antimony	Stibnite	Sb_2S_3	71
Bismuth	Bismuthinite	Bi_2S_3	81
Cobalt	Smaltite	$CoAs_2$	28
	Cobaltite	$CoAsS$	35
Mercury	Cinnabar	HgS	86
Molybdenum	Molybdenite	MoS_2	60
	Wulfenite	$PbMoO_4$	39
Tungsten	Wolframite	$(Fe,Mn)WO_4$	76
	Huebnerite	$MnWO_4$	76
	Scheelite	$CaWO_4$	80

Source of Data: January 1961, *Field Handbook For Mineral Engineers,* U.S. Dept. of the Interior, Bureau of Land Management.

Table 5

COMMON GANGUE MATERIALS

Class	Name	Composition
Oxides	Quartz	SiO_2
	Other silica	SiO_2
	Bauxite, etc	$Al_2O_3 \cdot 2H_2O$
	Limonite	$Fe_2O_3 \cdot H_2O$
Carbonates	Calcite	$CaCO_3$
	Dolomite	$(Ca,Mg)CO_3$
	Siderite	$FeCO_3$
	Rhodochrosite	$MnCO_3$
Sulfates	Barite	$BaSO_4$
	Gypsum	$CaSO_4 + 2H_2O$
Silicates	Feldspar	
	Garnet	
	Rhodonite	$MnSiO_3$
	Chlorite	
	Clay minerals	
Miscellaneous	Rock matter (sic)	
	Fluorite	CaF_2
	Apatite	$(CaF)Ca_4(PO_4)_3$
	Pyrite	FeS_2
	Marcasite	FeS_2
	Pyrrhotite	Fe_7S_8
	Arsenopyrite	$FeAsS$

Source of Data: January 1961, *Field Manual for Mineral Engineers,* U.S. Dept. of the Interior, Bureau of Land Management

The Formation of Iron Mineral Deposits

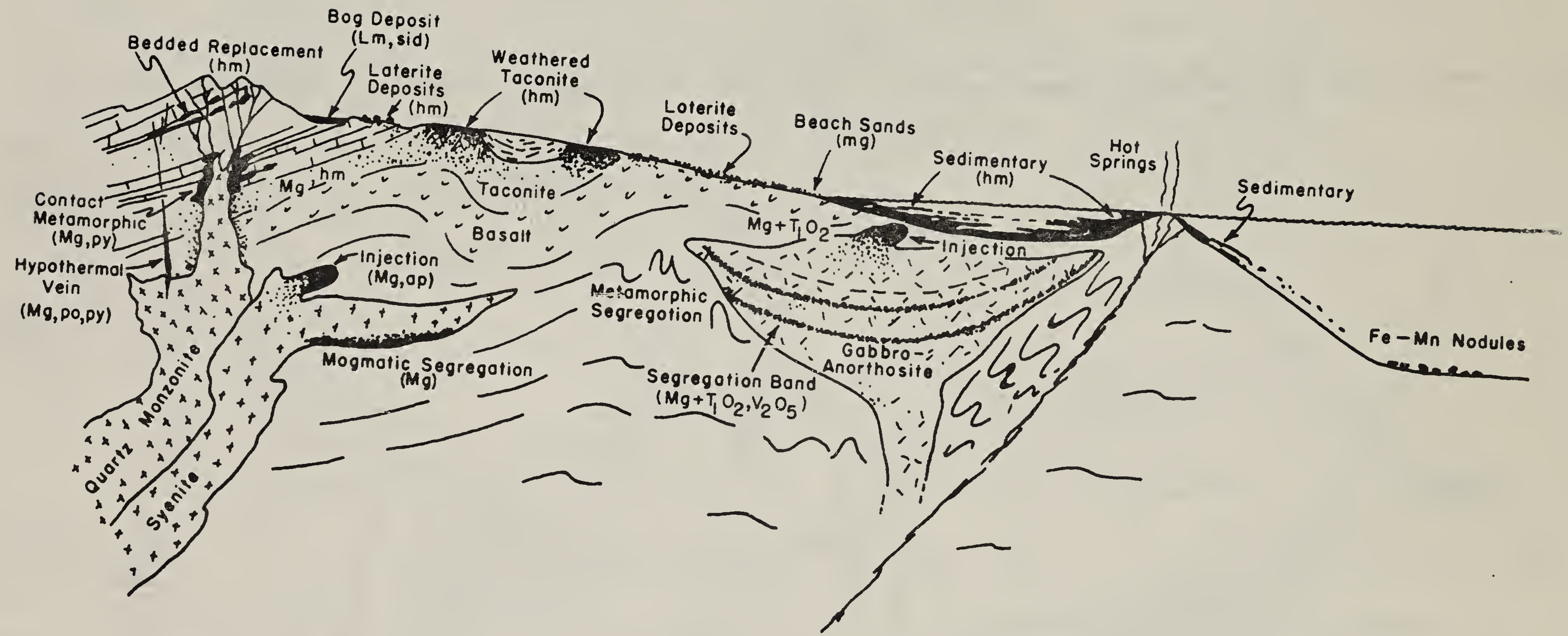


Fig. 13 - Various manners in which known economically usable concentrations of iron minerals have been created and the forms which such deposits take.

The Formation of Copper Mineral Deposits

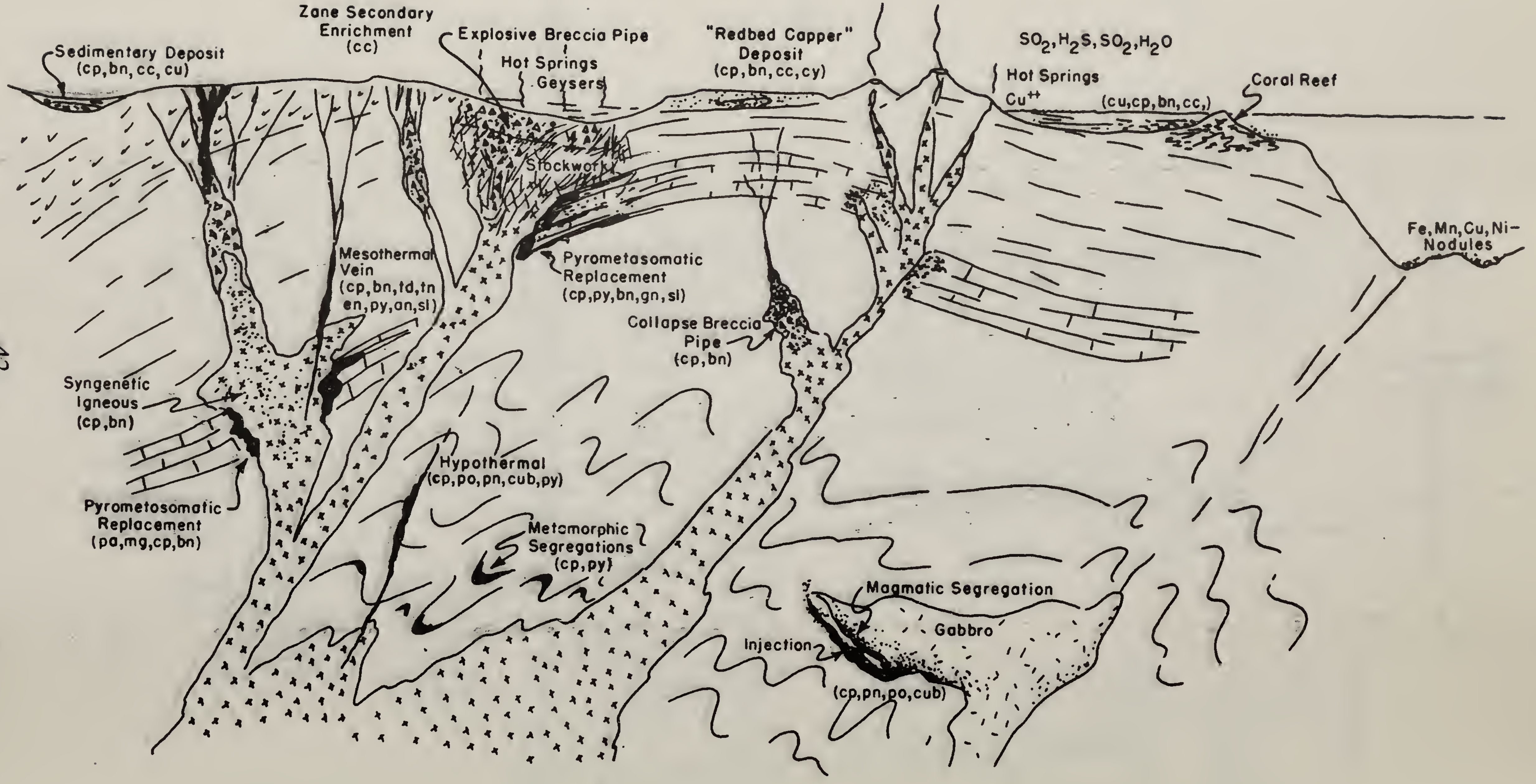

Sedimentary Deposit (cp, bn, cc, cu)
Zane Secondary Enrichment (cc)
Explosive Breccia Pipe
Hot Springs
Geysers
"Redbed Copper" Deposit (cp, bn, cc, cy)
SO_2, H_2S, SO_2, H_2O
Hot Springs
Cu^{++}
(cu, cp, bn, cc,)
Coral Reef
Stockwork
Fe, Mn, Cu, Ni-Nodules
Mesothermal Vein (cp, bn, td, tn en, py, an, sl)
Pyrometasomatic Replacement (cp, py, bn, gn, sl)
Collapse Breccia Pipe (cp, bn)
Syngenetic Igneous (cp, bn)
Hypothermal (cp, po, pn, cub, py)
Pyrometosomatic Replacement (pa, mg, cp, bn)
Metamorphic Segregations (cp, py)
Magmatic Segregation
Gabbro
Injection
(cp, pn, po, cub)

Fig. 14 - Ways in which commercially usable concentrations of copper minerals have been created and the forms in which such deposits occur.

The Formation of Lead, Zinc, and Silver Mineral Deposits

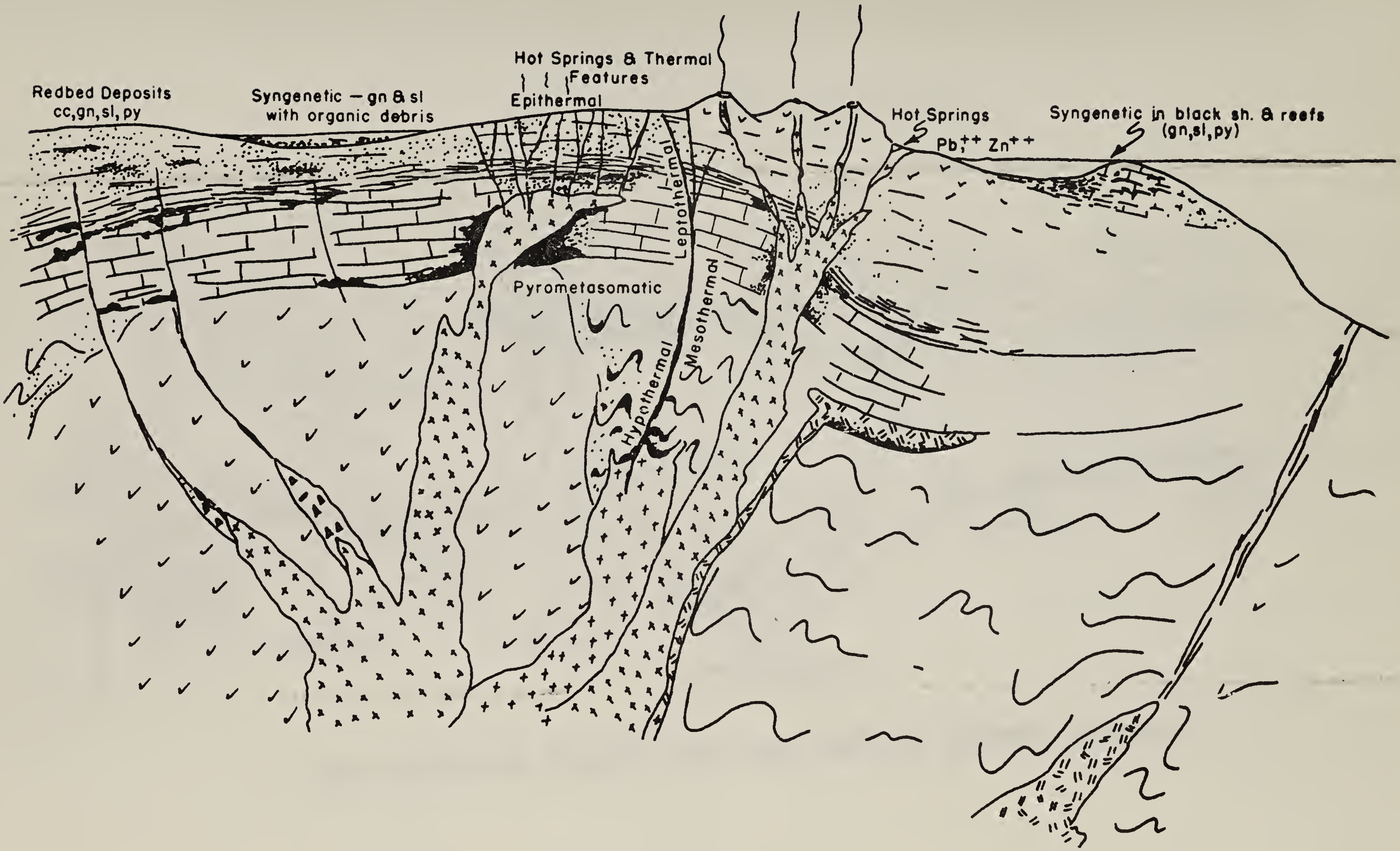


Fig. 15 - Ways in which known economic deposits of lead, zinc, and silver minerals have been created and the forms that presently known occurrences of such minerals take.

The Formation of Gold, Tin, and Tungsten Mineral Deposits

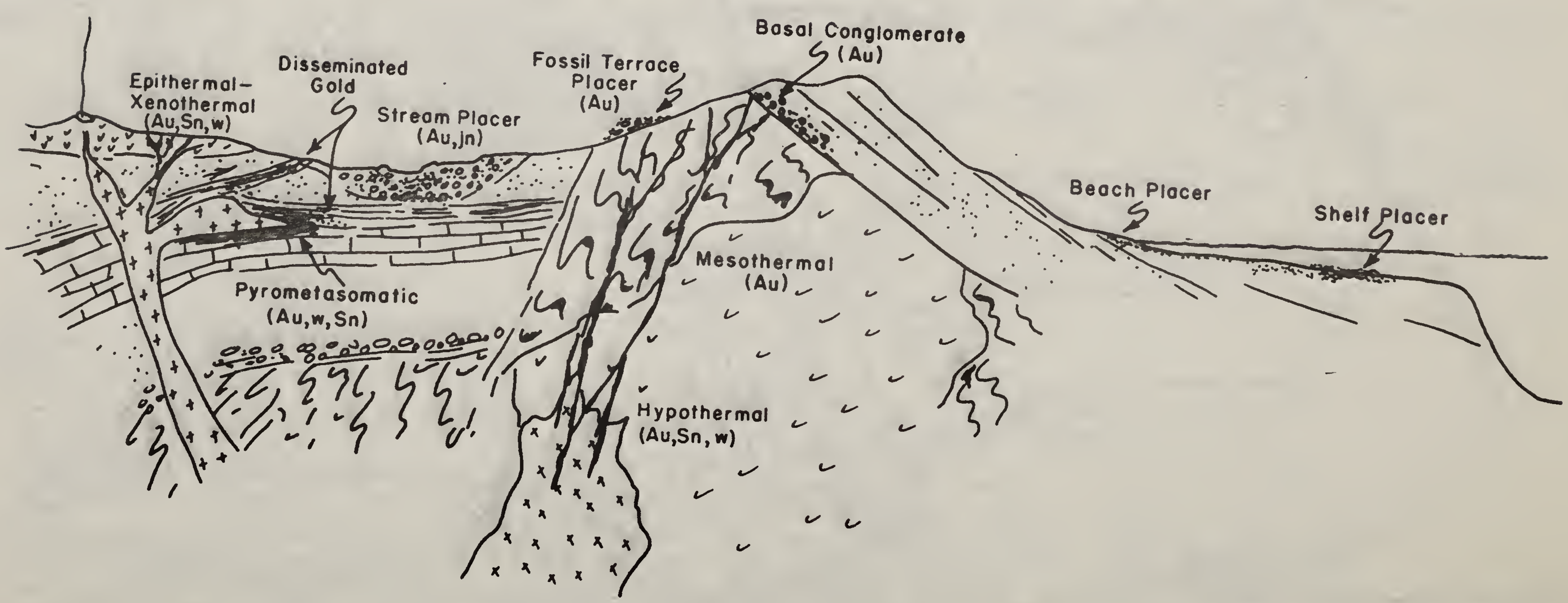
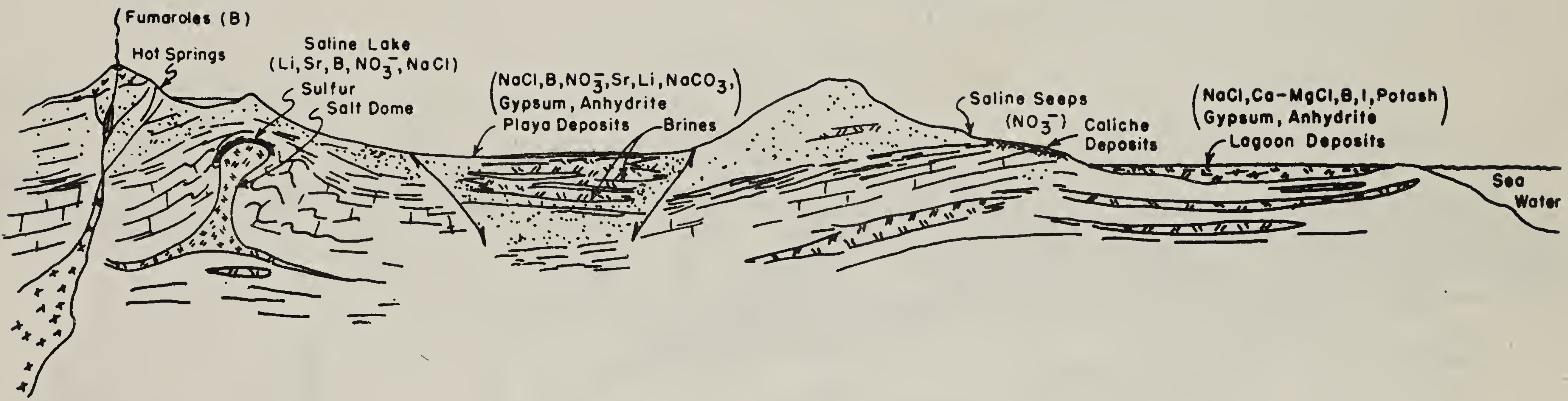
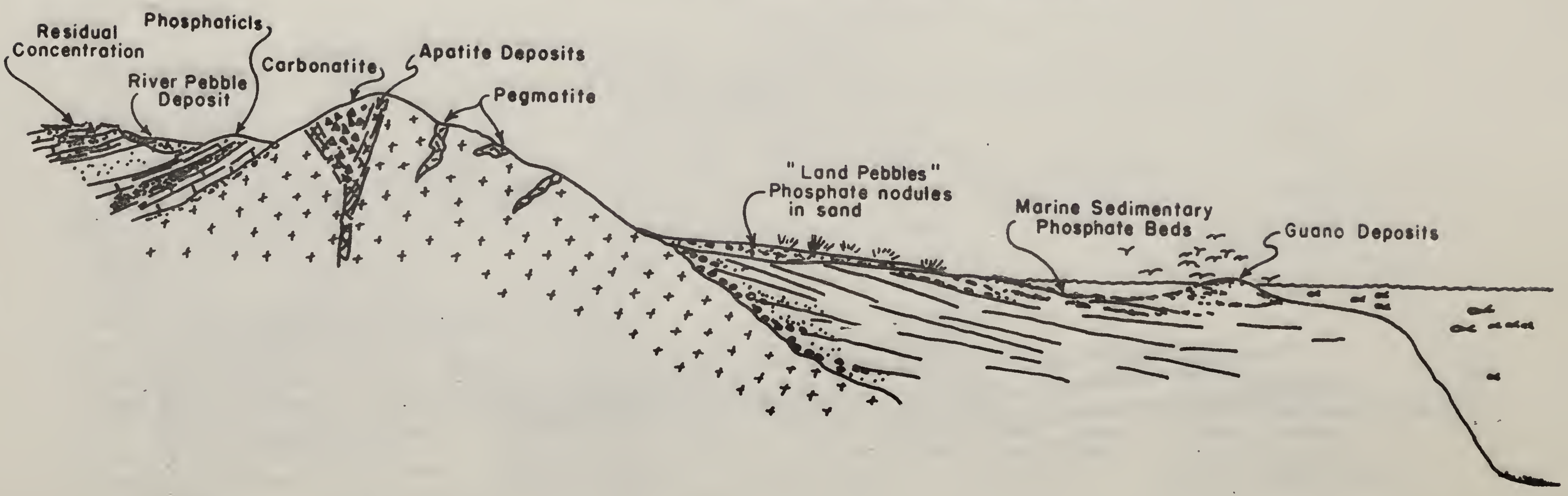


Fig. 16 - Ways in which commercially usable concentrations of certain heavy metals, including
and tungsten minerals, have



The Formation of Saline Deposits

Fig. 17 - Ways in which various mineral deposits have been formed and the circumstances under which commercially usable concentrations of various industrial minerals are normally found.



The Formation of Phosphate Deposits

Fig. 18 - Means by which economically valuable deposits of phosphate minerals have been formed and are known to occur.

The Formation of Calcium Carbonate Deposits

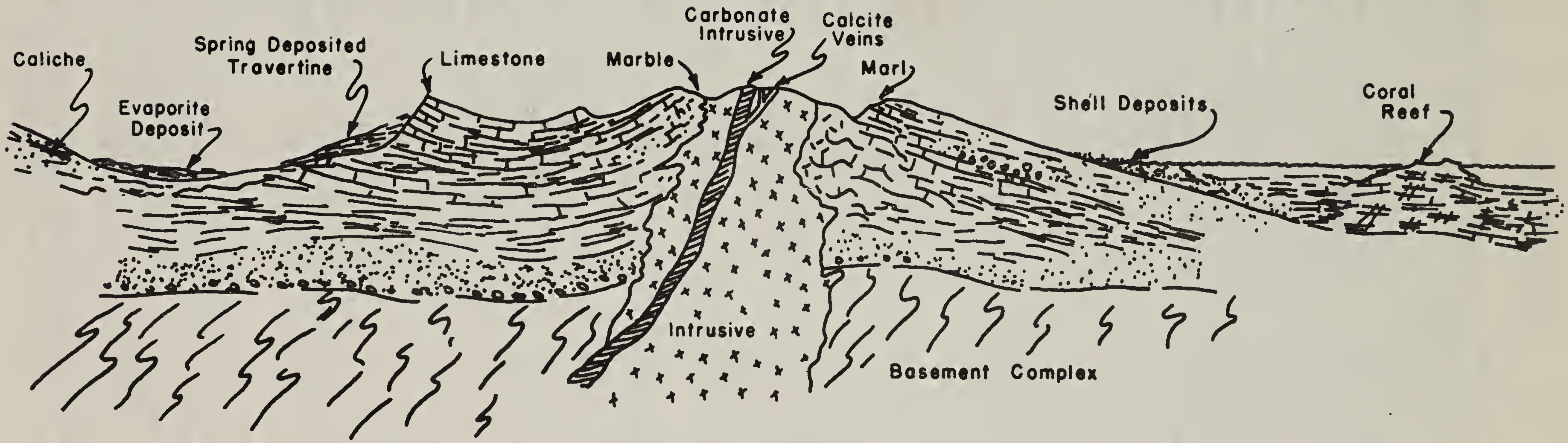


Fig. 19 - Ways in which deposits of calcium carbonate have been formed and the circumstances under which they are known to occur.

G. SUMMARY

The world would indeed be fortunate if all economically valuable mineral deposits were clustered around centers of consumption. But the world is not so fortunate. Mineral deposits occur in distinct areas as a result of the fortuitous combination of specific geologic environments and processes. These have neither operated equally in all parts of the world nor at the same time. Different types of economically valuable mineral deposits occur in different geologic environments. Finding a favorable environment, however, is no guarantee that an economically valuable mineral deposit will be found. The necessary geologic processes have only rarely resulted in the formation of particular mineral commodities in any one place in sufficient quantity and quality to be of economic value.

Forests can be harvested and replanted either in the same or in different areas to make room for urban and industrial expansion. Agricultural areas can also be moved. Wastelands can be reclaimed and reforested or used for farming and ranching. The progressive conversion of natural desert wasteland to grassland for cattle raising has been going on for years in the Big Bend area of Texas. Vast areas in the southeastern United States have been planted in forest since World War II and they now support a major timber industry. Cities and urban areas can be established wherever there is solid ground and even where there is not, as on reclaimed swampland or filled harbors.

If an area containing, or having the potential of containing, economic mineral deposits, however, is withdrawn from access for exploration and mining to accommodate urban, industrial, forest, park, wilderness, or other uses, part of the nation's useable mineral resources are lost at least as long as that withdrawal remains in effect, and perhaps forever. In Brazil, for example, deposits of iron oxides which were at one time economically valuable as a source of iron were withdrawn from use by government edict. Technology and economic conditions subsequently changed, and it is doubtful if under today's conditions those deposits would be considered economically valuable even if they were now made available for development and production. What once was a potential economic resource was thus kept in storage until it perished.

There is no constant size or composition of a mineral deposit which makes it an economically valuable deposit. Similarly, there are no constant or rigidly definable conditions of mining, processing, marketing, or distances from markets which make a particular mineral deposit economically valuable. In fact, it is only the ability of an individual or organization to mine and sell a mineral commodity that is the governing factor as to what is and what is not an economically valuable mineral deposit.

The established existence of a market for a mineral commodity is not an absolute criterion of the value of a deposit containing that mineral. For example, nickel was of little value until the companies owning nickel deposits demonstrated its varied uses, established a reliable source of supply at a reasonable price, and developed the markets for it. Similarly, the value of expandable clay deposits in California was nil prior to the development of the use of this type of clay in lightweight aggregates for construction purposes. Conversely, many common rocks and minerals contain aluminum and iron, metals for which there are already established markets. Nevertheless, many of the deposits in which iron and aluminum are found are not considered economically valuable at present because technology has not yet developed to the point at which anyone would buy those particular minerals as sources of those metals.

What is an economically valuable mineral deposit to one person may not be so to another. A small miner/operator can economically operate a small mine where he can remove and sell sufficient quantities of a valuable mineral commodity to pay for his own labor, whether the deposit be high-grade or low-grade. Larger companies, however, ordinarily require larger mineral deposits and larger markets to have a reasonably valuable operation.

Valuable mineral deposits (and the markets which really determine whether or not they are valuable) are highly variable in size and in economic potential. Consequently, there presently exists in the United States an extremely wide range in the size of mining operations and mining operators.

In addition to established market demand, initiative, resourcefulness, and good management in both mineral production and marketing often make the difference between valuable mineral and waste. For example, the Bluebird disseminated copper deposit near Miami, Arizona, is relatively low in copper content and relatively small for this type of mineral deposit. Prior to 1964, it had been rejected as not being economically valuable by several large and small companies because they considered it too costly to mine. Amid dire predictions of failure by knowledgeable elements of the mineral industry, Ranchers Development Company of Albuquerque, New Mexico, acquired the Bluebird property. Through extensive study, relatively inexpensive methods of mining and extraction were developed which could be applied to that particular mineral deposit, and the Bluebird mineral deposit was made into an economically valuable resource and a source of personal income for workers and owners alike.

Changes in demand, technology, and competitive sources of supply all affect the classification of specific mineral deposits as valuable or not valuable for any given period of time. Prior to World War II, uranium was in small demand. The development of nuclear fission and subsequent national defense and research requirements created a larger market for uranium from 1945 until the mid-1950's when demand from these sources began to diminish. In the late 1950's, therefore, the subsequent discovery of new uranium deposits was of little concern or value to all but the more foresighted individuals and companies until 1964, when it became obvious that demand for uranium in civilian uses was beginning to accelerate. Now certain mineral deposits containing uranium are again economically valuable.

Cyclical changes in price and in supply have been maintained by foreign producers in mercury, tungsten, and manganese. The classification of domestic deposits of these metals as valuable or not valuable has fluctuated accordingly. While changing technology is creating demand for new mineral commodities (the rare-earth elements in the manufacture of television tubes, for instance), it is also enabling the low-grade or waste of yesterday to become the ore of today or of the future. For example, improved methods of molybdenum and copper recovery have enabled the Duval Corporation to make a mine out of the relatively low-grade Esperanza copper-molybdenum deposit south of Tucson, Arizona. Other examples are legion.

The search for, acquisition of, and retention of valuable mineral deposits is based on the premise that a sufficient quantity and quality of a *valuable mineral* may be found which, through research and development, may become an *economically valuable mineral deposit* under favorable present or future conditions. The mineral industry bypasses or ignores, however, specific areas or mineral commodities when it has been made too difficult or impossible to acquire or retain necessary lands long enough to conduct sufficient exploration, research, and development to determine whether or not a valuable product can be made from a mineral deposit. For example, in 1959-1960 the Sunrise Mining Company conducted exploration for perlite in connection with the development of a broadly-based industrial minerals operation. Upon learning that the Department of the Interior was challenging the locatability and value of perlite, exploration was immediately diverted from federal lands to less-promising areas in New Mexico on state lands where acquisition and retention for mineral exploration and development could be assured.

The prices of mineral commodities and their costs of production change continually, and costs are also variable from mine to mine. Consequently, the designation of a particular grade of rock as valuable or waste is valid only for a specific mining operation during a specific time interval. If prices fall or costs go up, the necessary valuable mineral content of the rock must rise, for it to be considered a valuable mineral deposit. It is often true that last year's ore may be this year's waste but next year's ore again, and that one mine's ore may be another mine's waste.

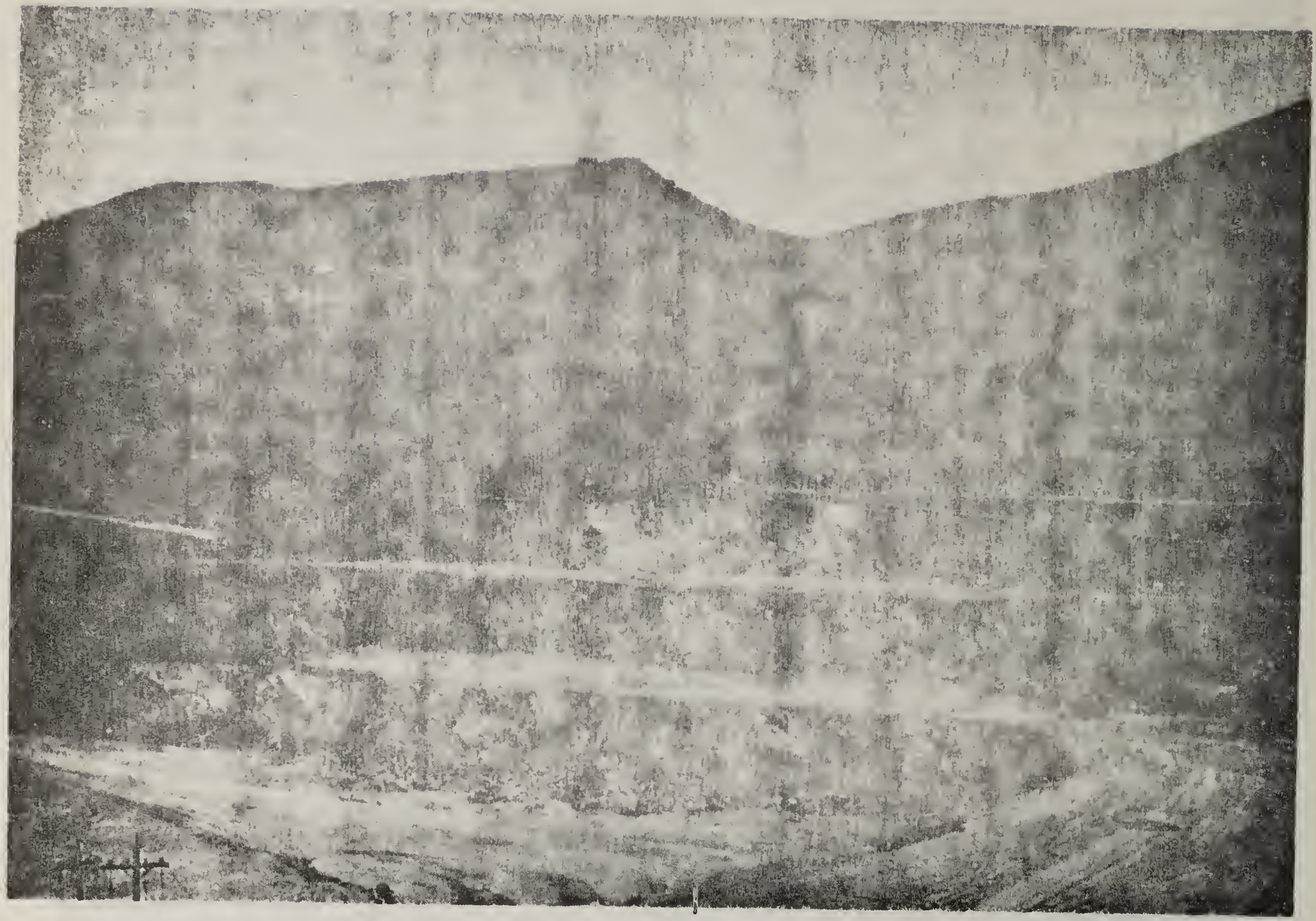


Fig. 20 - Surface mining operations at the Lavender Pit of the Phelps-Dodge Corporation at Bisbee, Arizona. Located above the deeper and higher-grade massive copper sulfide replacement deposits worked first by underground methods in the late 1800's, this relatively low-grade porphyry copper deposit was not considered ore until advancing technology made extraction feasible in the 1950's.

CHAPTER 3

THE GEOLOGY OF THE UNITED STATES

Does that part of the United States west of the 105th Meridian (except Alaska and Hawaii) have geological characteristics significantly different from the eastern part of the nation? Do any such differences include the existence of some minerals which may not be considered valuable at present but which could become commercially productive by 1985?

A. THE GEOLOGY OF THE UNITED STATES

The United States may be considered geologically as consisting of five major areas. The largest of these is the *Western United States* extending from the Great Plains westward to the Pacific. The *Interior Plains,* extending from the Front Range of the Rockies eastward across the Missouri, Mississippi and Ohio Valleys to the Appalachians, form the second largest region. The third major region is the *Appalachians,* including not only the mountains themselves but the rolling plateau to their west and the Piedmont region to the east.

Two other geologic areas lie to the north and south of the Interior Plains province. On the north is the portion of the *Canadian Shield* which extends northward to cover nearly two-thirds of Eastern Canada. On the south and east is the *Atlantic Coastal Plain.* All of these general areas are shown in Figure 21.

The rocks and geologic structures at and near the surface vary noticeably from one major area to another. The youngest geology is found on the Atlantic Coastal Plain where unconsolidated sediments of recent Cenozoic age are common. The oldest geology is found in the Canadian Shield area where virtually the only remaining rocks and structures are of Precambrian age. Throughout the Appalachian Region and across most of the Interior Plains, the rocks and geologic structures are of Paleozoic age. On the western plains and throughout the entire Western United States, the surface and near surface rocks are mostly of Mesozoic and Cenozoic age. In the West, only in limited places, such as at the bottom of the Grand Canyon, are rocks as old as Precambrian exposed at the surface.

Just as the ages of the rocks in the various areas differ, so also do the prevalent types of rocks. On the Atlantic Coastal Plain, the surface is covered to considerable depth not with rock at all but with unconsolidated sediments. In the Canadian Shield, the rocks are nearly all metamorphic. Throughout the Interior Plains and Appalachian regions, sedimentary rocks are most common although there are also significant occurrences of metamorphic and intrusive igneous rocks in the Appalachians. In the West, all types are found with extrusive igneous rocks and sedimentary rocks being perhaps the most common. Broad areas of the West, particularly in the Basin and Range province of the Southwest, are also covered by considerable expanses of unconsolidated sediments.

The dominant geologic structures likewise differ from one geologic area to another. On both the Atlantic Coastal Plain and in the Interior Plains, beds of sedimentary rock are relatively horizontal with some slight tilting but little or no folding or faulting. In the Canadian Shield and particularly throughout the Appalachians, extreme folding has made synclines and anticlines the dominant geological structures. In the West, geologic structures are far more varied. In some areas flat-lying sedimentary beds dominate, as on the Colorado Plateau. In other areas (e.g., the Columbia Plateau), broad, horizontal extrusive structures are common. In still others, large intrusive structures such as the Sierra Nevada and Idaho Batholiths predominate. Throughout the Basin and Range province, folds and faults combine with igneous intrusives to provide the dominant geological structures.

The varying geologic events and environments in the different areas of the United States have had significant influences on the processes of mineral deposition in those areas. The variations in mineral deposit formation appear to be most closely related to the geologic histories of those areas. Just as does the political history of the nation, the geologic history of the United States seems to start in the East and extend westward.

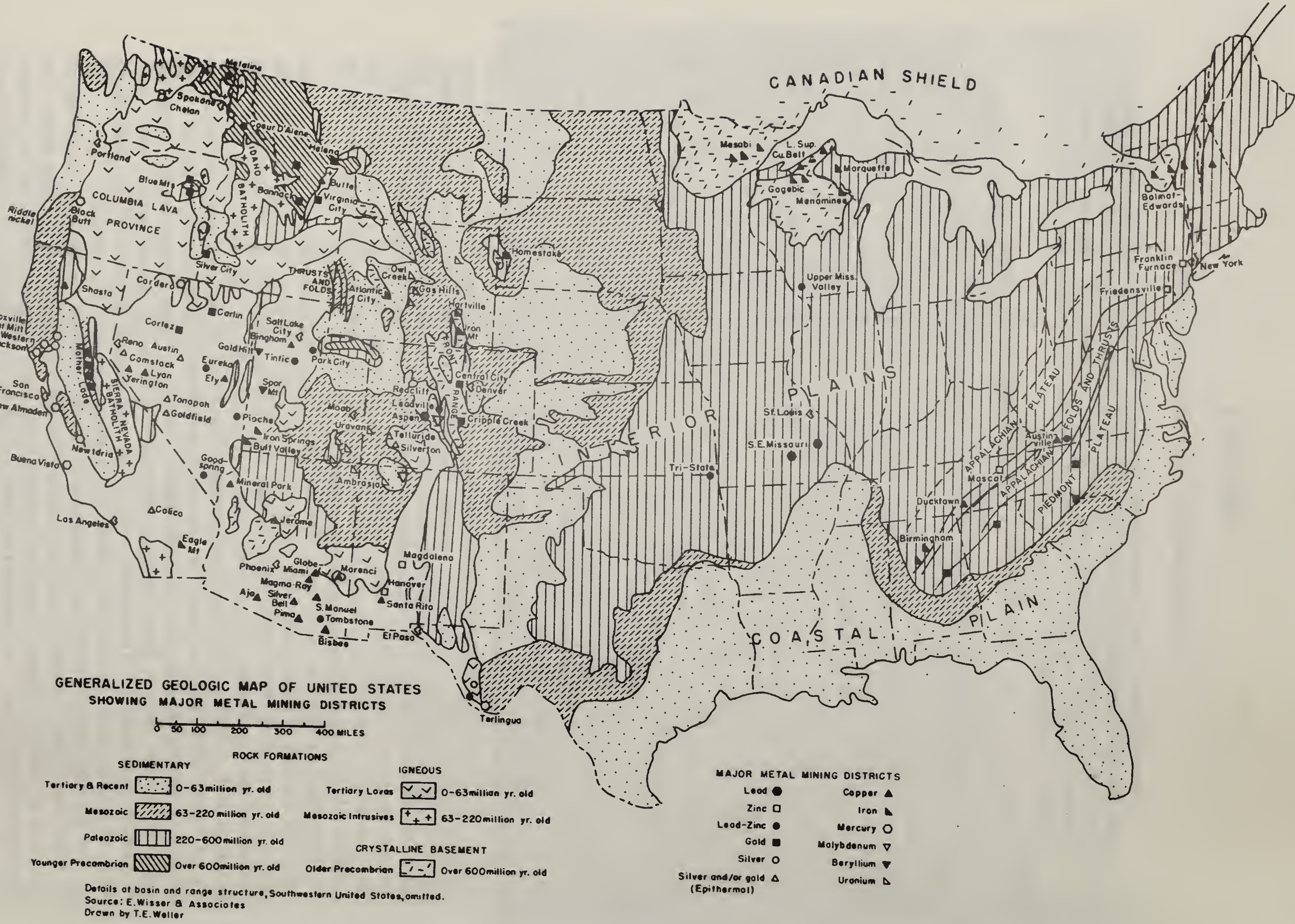
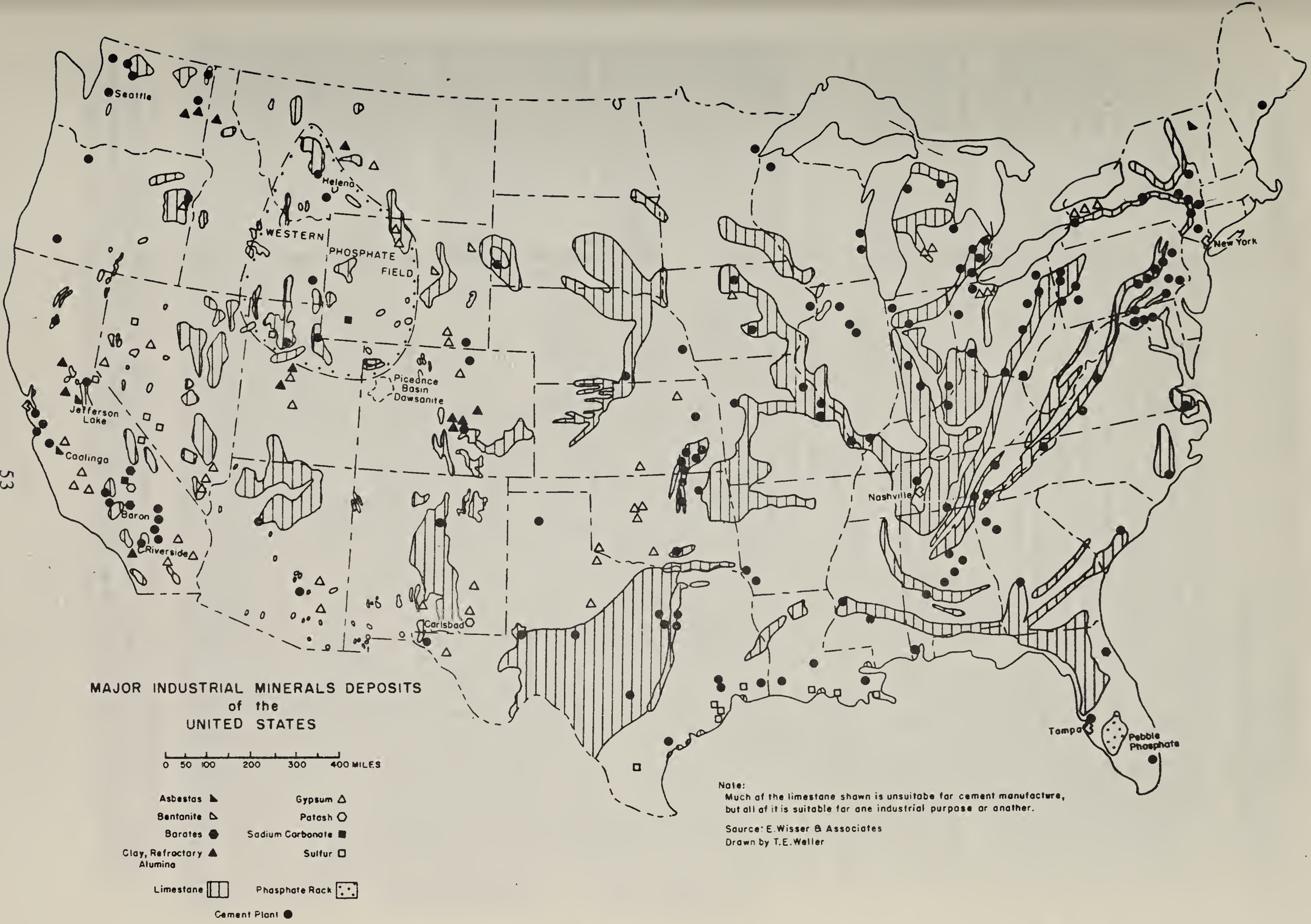


Fig. 21 - A generalized geologic map of the United



MAJOR INDUSTRIAL MINERALS DEPOSITS
of the
UNITED STATES

Note:
Much of the limestone shown is unsuitabe for cement manufacture,
but all of it is suitable for one industrial purpose or another.

Source: E.Wisser & Associates
Drawn by T.E.Weller

Fig. 22 - A generalized geologic map of the United States showing the location of principal limestone deposits and major industrial minerals operations.

B. THE FORMATION OF MINERAL DEPOSITS IN THE UNITED STATES.

1. Earliest Mineral Deposition

The greatest area of exposed rocks of Precambrian age in North America covers nearly two thirds of the eastern and far northern portions of Canada. This area, known as the Canadian Shield, was the site of intense orogeny, intrusion, and mineralization in Precambrian time. Since then, however, the area has been stable and only lightly covered with younger sediments.[31] The southeasternmost portion of the Canadian Shield lies within the United States, extending from Maine westward to Northern Minnesota. Actually, the older Precambrian basement complex underlies the entire United States, but, except in the extreme northeastern part of the nation where it has been uplifted and scraped by glaciers, it has been depressed below sea level so that Palcozoic, Mesozoic, and Cenozoic sediments have been deposited on top of it.

Although younger sediments once covered all of the older Precambrian basement complex in the Western United States, great vertical uplifts have raised blocks of it far above sea level, exposing them to erosion, and stripping off the cover of younger sediments. Prime examples are the Front Range of the Rockies and many areas in Arizona, including the lower rocks in the Grand Canyon. The Precambrian age rocks of the Canadian Shield have yielded immense quantities of iron, nickel, copper, lead, zinc, silver and gold, and these deposits were evidently formed during Precambrian time.

For many years most of the iron ores produced in the United States have come from the Precambrian age rocks of the Lake Superior district. The high-grade ores are now exhausted, but there are still immense reserves of low-grade siliceous magnetic iron-bearing rock, called ***taconite,*** from which the magnetic iron oxide, ***magnetite,*** can be removed by magnetic beneficiation methods. Taconites of Precambrian age also occur in Montana, Wyoming, and Arizona.[32] A taconite deposit containing at least 300 million tons of iron-bearing rock is in fact yielding iron ore at Atlantic City, Wyoming.[33]

Precambrian age copper deposits have been mined for over 100 years in the Lake Superior region of the Canadian Shield and reserves are by no means exhausted. The magnetic iron ores of Northern New Jersey and the titanium-bearing iron ores of the Adirondacks in Northern New York are Precambrian in age, as are the talc and soapstone deposits of Western New York. The lead-zinc deposits at Edwards and Balmat, New York, and the zinc deposits of Franklin, New Jersey, also lie in Precambrian rocks and are very probably Precambrian in age.[34]

Aside from the taconite deposits, Precambrian age ore deposits are few in the West, but three have been of prime importance. These include the large and rich copper deposits at Jerome, Arizona[35], and the nation's principal gold producer, the Homestake Mine in the Black Hills of South Dakota.[36]

In younger Precambrian time crustal sagging produced a geosyncline (a long trough), permitting the entry of the Pacific Ocean and forming a long, narrow seaway extending southward from Canada through Idaho, Western Montana, Wyoming, Utah, Western Colorado, Arizona and Southern California. Shales, limestones, and sandstones were deposited in this trough.[37] The great silver-lead-zinc ore deposits of the Coeur d'Alene district in Idaho occur in the younger Precambrian quartzites formed in this geosyncline. Until recently it was supposed that these deposits were formed in Mesozoic time, but laboratory methods to determine the age of minerals and rocks in millions of years now suggest that these ore deposits date from Precambrian time.[38]

2. Paleozoic Mineral Deposition

The Paleozoic Era, which followed Precambrian time, was the vital era for orogeny, intrusion, and mineralization in the Eastern United States, except for those areas in the Canadian Shield. In the West, such events were almost wholly lacking in the Paleozoic Era.[39]

At the start of the Paleozoic Era, the Appalachian geosyncline started to sag (its position is shown by the belt of folds and faults shown on the map in Figure 21). Thick sediments were deposited in the trough as it continued to sag. At the same time, thinner sediments were laid down to the west, in the more stable interior portion of the continent.

Geosynclines are typically belts of intense deformation associated with intense folding and faulting. The first such deformation of the *Appalachian Geosyncline* occurred in the early Paleozoic Era about 400 million years ago. This period of deformation, called the *Taconian Disturbance,* was restricted to the northern portion of the Appalachian Geosyncline. Although the effects of the disturbance have not been traced so far south, it is thought that the enormous zinc deposits of the Mascot district in Eastern Tennessee were formed at this time.[40] These are at present among the largest known reserves of zinc ore in the United States. Approximately 150 million years later, the Appalachian trough was intensely deformed again, during what is known as the *Acadian Disturbance.* At least in New England, this disturbance was accompanied by granite intrusions.[41] The copper deposits of Vermont were probably formed at the time of this disturbance.[42] About 440 million years ago, before the Taconian Disturbance, iron-bearing sedimentary beds were deposited in the Appalachian geosyncline belt from New York to Alabama. These *Clinton iron ores* are generally too thin to be commercial, but where they are thick, as at Birmingham, Alabama, they have been mined extensively.[43]

At the close of the Paleozoic Era, about 200 million years ago, a land mass then existing on the east side of the Appalachian geosyncline moved westward, wiping out the trough and intensely folding and faulting the thick sediments deposited within it. A great mountain

Fig. 23 - Underground mining operations in the Coeur d'Alene district of Northern Idaho. The rich silver-lead-zinc deposits of the area were formed during Precambrian time and represent some of the oldest mineral deposits known to exist in the Western United States. Gold deposits in South Dakota, and the copper deposit at Jerome, Arizona, were also formed during Precambrain time.

chain, the Appalachians, was formed, extending from Newfoundland to Alabama, and this movement of the earth's crust has been called the *Appalachian Revolution.* In the piedmont area, east of the belt of intensely folded rocks that formed the backbone of the mountain chain, extensive intrusions of granite occurred.[44]

Metallic mineral deposition has been commonly associated with the closing stages of major deformations such as the Appalachian Revolution and with the igneous intrusions common in those stages. Many gold deposits are scattered along the piedmont belt of schists, slates, and granitic intrusions in what are now the Carolinas and Georgia. These gold deposits are probably of latest Paleozoic or earliest Mesozoic age and thus were formed either during the waning stages of the *Appalachian Revolution* or shortly after it. Many other eastern ore deposits were probably formed at the same time. In the Tri-State zinc-lead district of Kansas, Missouri, and Oklahoma, a late Paleozoic Era uplift in the earth's crust fractured the limestone existing there and gave access to solutions which deposited zinc and lead sulfides in the openings. Although a considerable distance west of the site of the major uplifting caused during the Appalachian Revolution, the Tri-State district mineralization probably dates from the same time.

In the Western United States, the younger Precambrian geosyncline mentioned previously as extending from Canada to the Gulf of California persisted into the Paleozoic Era. Known as the *Cordilleran Geosyncline,* this seaway was much broader than the Appalachian trough. On its eastern slope, limestone, clean sandstone, and shale were deposited, while on the west, impure sandstone, chert (silica) and other sediments were laid down, together with volcanic flows. In the later Paleozoic Era, about 340 million years ago, a long upward ridge or *geanticline* formed, which crossed Nevada northeastward into Idaho and separated the former broad seaway into two roughly parallel troughs. In the one of the east, limestone, sandstone, and shale were deposited, while in that on the west, chert and volcanics were laid down.

At the same time, faulting occurred and masses of rock were shoved eastward for miles over the eastern sediments, along a great flat fault known as the *Roberts Mountains Thrust.* No intrusive activity or ore deposition accompanied this orogeny,[45] but the geanticline or great ridge formed by the disturbance persisted into times of later mineralization and had a strong effect on localizing particular mineral deposits.

3. Mesozoic Mineral Deposition

Both the eastern and western seaways of the Cordilleran Geosyncline persisted into the Mesozoic Era. The geanticline or great ridge, trending north-south through Eastern Nevada and Western Utah, rose intermittently counteracting its wearing away by erosion. About 160 million years ago, in the earlier half of the Mesozoic Era, what is now Southern Arizona was uplifted, deformed and intruded by granitic rocks. The great copper deposits of Bisbee came into existence at this time.[46] Next came the far more widespread *Nevadan Revolution,* which started about 145 million years ago, when the great north-south geanticline passing through Nevada started to rise. Granitic rocks were intruded along its length and metallic mineral deposition began within it. Such deposition started probably with the contact metamorphic copper-lead-silver deposits now known to exist in Northeastern Nevada.

As it rose, the western edge of the geanticline moved westward. Occupying the present site of the Sierra Nevada Range in California there had been another trough or geosyncline that was similar to the Appalachian trough of Paleozoic time. The thick series of bedded rocks in this *California Trough* became intensely folded and faulted with the deformation extending northward to the Shasta District in Northern California. Granitic rocks intruded the overlying rocks in both the geanticline and the California trough, and the zinc-copper deposits of the Sierra Nevada foothills as well as the copper-zinc deposits of the Shasta District were probably formed at this time. The geologic effects of the Nevadan Revolution were not limited to Nevada and California, however. The intrusion of igneous material in the

Blue Mountains area of Oregon began at this time. The gold deposits of this part of Oregon apparently also date from this period, although the great Mother Lode gold belt of California is believed to have formed somewhat later.

The eastern seaway of the Cordilleran Geosyncline persisted during the Nevadan Revolution as a broad, shallow interior sea, undisturbed by deformation or intrusions. In the central geanticline, greatly expanded and still vigorously rising, intrusion and metallic mineral deposition continued. The copper district of Ely, Nevada, toward the eastern edge of the geanticline, came into being 120 or 110 million years ago. Toward the western edge of the geanticline, Yerington's copper deposits date from about the same time.

The great granitic intrusions of Western North America, the batholiths, were intruded about 100 million years ago.[47] These include the *Idaho Batholith,* the *Sierra Nevada Batholith,* and the *Southern California* (or *Baja California) Batholith.* Unlike many smaller intrusions, these very large intrusions seem to have had no direct effect on metallic mineral deposition. Although the exact age of the *California Mother Lode,* a north-south belt of gold-quartz veins over 100 miles long, just west of the Sierra Nevada Batholith, is not known, it was probably formed not long after consolidation of that batholith.[48] While gold production from the Mother Lode was very large, the ore was relatively low-grade and only producible with the low mining costs prevalent at the time.

Many geologic disturbances occurred in the Western United States, from the time of the Nevadan Revolution on, but deformation and mineralization reached a climax in the Laramide Revolution, about 70 to 50 million years ago. This revolution occurred toward the end of the Mesozoic Era and the beginning of the Tertiary period. The Laramide Revolution took place largely in the region east of the area affected by the Nevadan Revolution in what is now the Rocky Mountain region. The broad interior sea that had existed during the Mesozoic Era was wiped out by the uplift of its floor. Blocks such as the Rocky Mountain Front Range were differentially uplifted. Stong folding and flat faulting took place in beds of thick sediments, such as those along the western border of Wyoming. Many small granitic masses were intruded and many of these were closely associated with metallic mineral deposition.

Metallic mineral deposits arrived in a swarm with the Laramide Revolution. Among those that were formed first were the silver-lead-zinc deposits at Tombstone, Arizona (formed about 72 million years ago), followed by the Mineral Park porphyry copper deposit in Northwestern Arizona (71 million years ago), the San Manuel porphyry copper deposit (69 to 65 million years ago), the Santa Rita, New Mexico, porphyry copper deposit (65 million years ago), the Ajo, Arizona, porphyry copper deposit (63 million years ago), the Ray and Pima, Arizona, porphyry copper deposits (60 million years ago) and the Morenci, Arizona, porphyry copper deposit (55 million years ago). In Colorado, the Leadville silver-lead-zinc deposits together with the belt of gold and silver deposits extending northeast from Leadville across the Front Range date from about 63 million years ago. The great Butte copper deposits in Western Montana probably date from about the same time. Somewhat later (about 49 million years ago) came the Bingham, Utah, porphyry copper and adjacent silver-lead-zinc replacement limestone deposits, and the Tintic, Utah, intrusion and silver-lead-zinc replacement limestone deposits. In Nevada, intrusion and mineralization in the Eureka silver-lead-zinc district took place some 64 million years ago.

In the Eastern United States, the newly-born Appalachian mountain-chain was reduced by erosion during the Mesozoic Era. Extensive faulting took place, but there was little igneous activity and no known mineral deposition. By 70 million years ago, the show was over in the Eastern United States.

Toward the close of the Mesozoic Era, the last great submergence of the North American continent took place. During this submergence a great interior sea extended from the eastern border of Nevada as far east as Iowa. It covered most of Mexico and extended into the Eastern United States over what is now the coastal plain area. This great encroachment of the sea was wiped out by the emergence of the land before the end of Mesozoic time, when the North American continent assumed essentially its present form.[49]

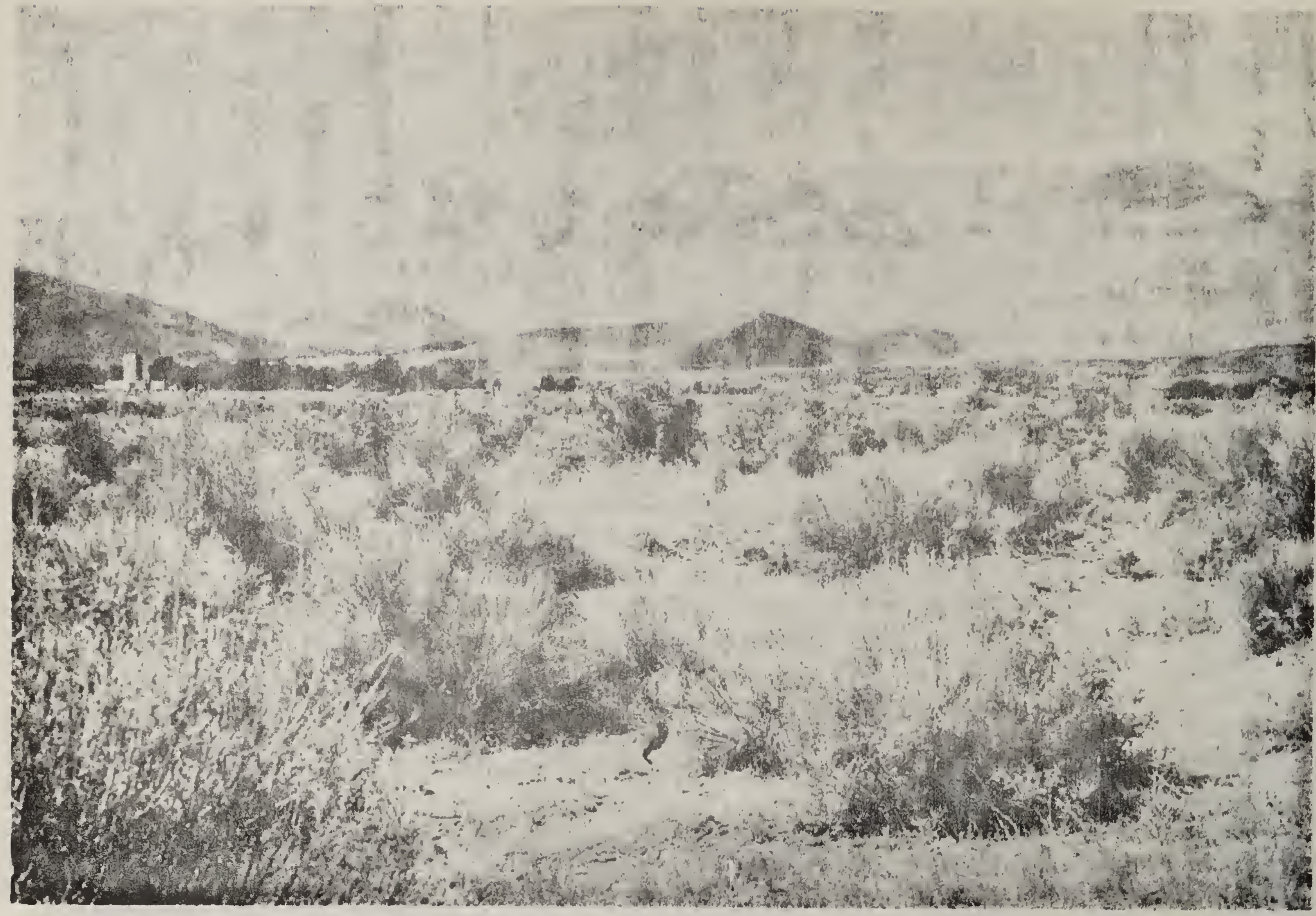


Fig. 24 - Part of the Sierra Nevada Batholith near Bishop, California, on the eastern edge of what is now the Sierra Nevada range. This large granitic mass was intruded into overlying rocks about 100 million years ago. Although apparently not the direct cause of mineral deposition, many mineral deposits, particularly those of heavy metals such as gold and tungsten, are found around the edges of such formations.

In the Eastern United States at the time of the Laramide Revolution in the West, deformation was limited to the uplift of the present Appalachian Mountain chain and associated areas. The chain was being eroded as it is today. No known intrusions nor mineralization took place. In the central interior of the continent, matters were even quieter. The surface was being reduced to its present form by long-continued, gradual stream erosion and by mass wasting.[50] This quiet Mesozoic and Tertiary period in the East was in marked contrast to the strong deformation, extensive igneous activity, and widespread mineral deposition that was going on in the West.

4. Cenozoic Mineral Deposition

In the West, after the waning of the *Laramide Orogeny* in the early Tertiary Period, the most significant geologic events were the extrusion of great sheets of lava, faulting on a tremendous scale, lifting and depressing blocks of the crust, and the widespread deposition of the so-called *epithermal* metallic mineral deposits. These took the form of silver-and/or gold-bearing veins, usually associated with volcanic rocks, with the mineral deposits formed not far below the existing surface. Examples are the Comstock Lode, Gold field, and Tonopah in Nevada, and Telluride in Colorado. The silver-and gold-bearing veins at Telluride contained base-metal minerals at depth, and they are presently known as deposits of lead and zinc.

Although the typical epithermal precious metal districts are now mostly exhausted, discoveries have recently been made of a type of gold deposit which is probably (but not certainly) Tertiary in age and epithermal in origin. The first such discovery was that of the Carlin gold deposit in Northeastern Nevada where specks of gold, invisible to the naked eye, lie in ordinary-looking sediments. The deposit, discovered in 1962, is now a successful open pit mine. A similar gold deposit has been found near Cortez, Nevada, and chances seem excellent for discovery of still other Carlin-type deposits, so that potential reserves of this type of gold mineralization may be very large. Toward the very end of the Tertiary period came the formation of mercury deposits in California, Nevada, Oregon, and Texas.

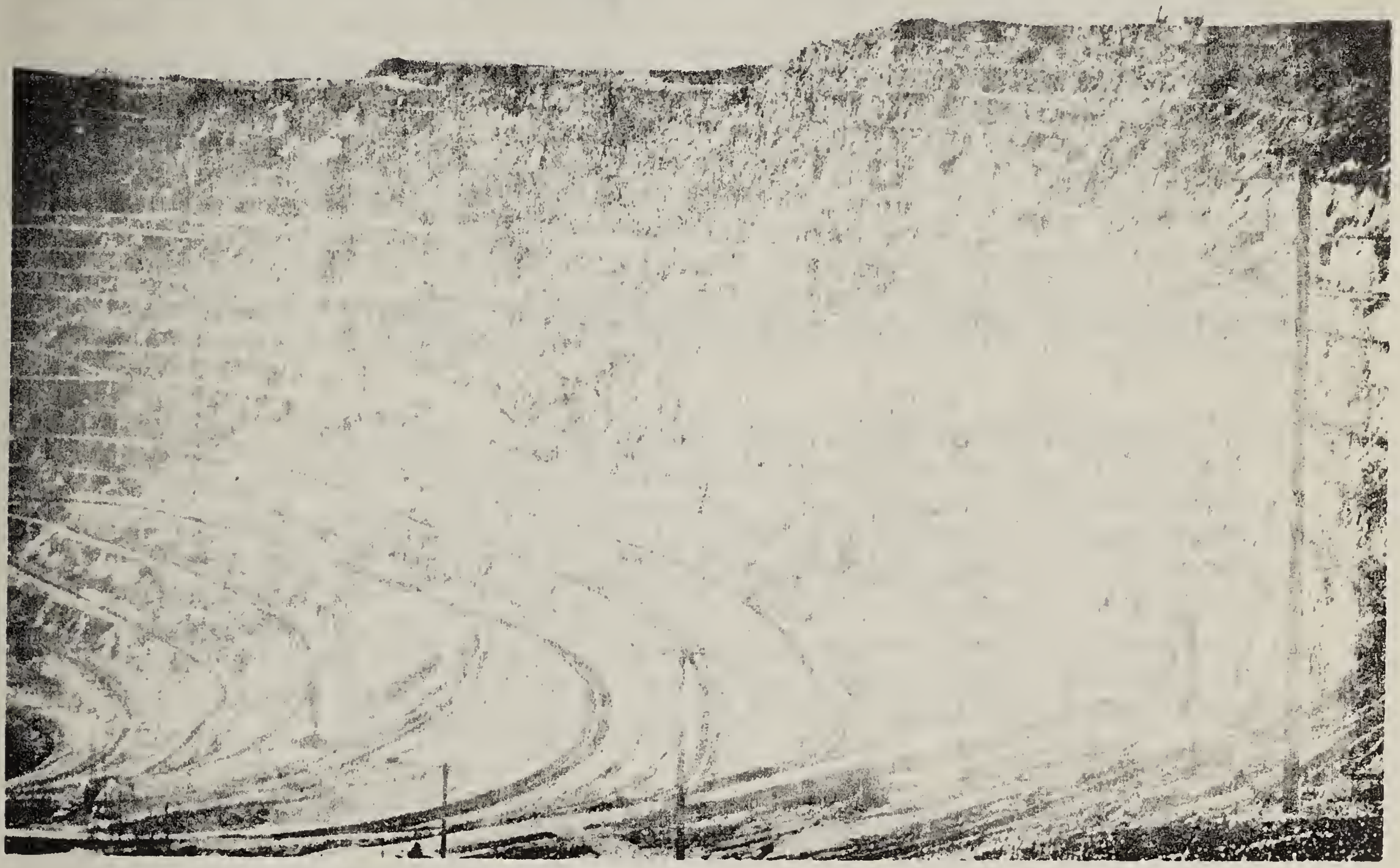


Fig. 25 — The porphyry copper deposit at Ajo, Arizona, one of many such deposits formed in the Western United States about 60 million years ago during the Laramide Revolution.

C. SUMMARY

That part of the contiguous 48 United States west of the 105th Meridian (i.e., west of the Great Plains) does have geological characteristics significantly different from the remainder of the nation. The surface and near-surface rocks in the West are generally younger than those in the East and they have been faulted and intruded extensively. Nevertheless, they are generally not so intensely folded or metamorphosed as are the rocks in the states east of the Mississippi. They have been much more disturbed, however, than the rocks covering the middle of the continent. Volcanic activity has been much greater in the West.

There are other differences between the geology of the West and the rest of the country, but there are also some similarities. Both areas possess extensive deposits of sedimentary rocks including limestone of varying grades. Although the mountains in the East are older and have been subjected to weathering and erosion for a greater length of time, the Appalachians and many of the mountains of the West were formed by similar tectonic forces exerted at different times and to different degrees.

Based on the history of mineral discovery over the past 200 years, there is little doubt that both the East and West possess some minerals that may not be considered valuable now but which could be so considered within the next 15 years. Some mineral deposits are not now known to exist, while others are known to exist but in concentrations too low for commercial utilizations, and still others are known to exist but are considered only as curiosities as uranium and zeolites once were. Many valuable mineral deposits undoubtedly lie hidden beneath overlying sediments, or lava flows, or vegetation. As one authority has noted,

> "The potential number of such districts is great. A large proportion of the earth's surface is blanketed by young sedimentary formations and by recent lava flows. How many Guanajuatos lie concealed beneath the rhyolitic capping of the Sierra Madre of Mexico? How many Kirkland Lake Districts are under the drift-cover of the Canadian Shield? How many Wilunas are still hidden by the alluvium of the desert of Western Australia? How many ore deposits lurk underneath the basalt-covered plateaus of the Columbia River region? If erosion at Goldfield, Nevada, had stopped 100 feet higher, probably no ore would have been exposed. How many Goldfields are still awaiting discovery?" [51]

FOOTNOTES

31/ C. Dunbar, *Historical Geology,* New York: John Wiley and Sons (1949), pp. 91-92.

32/ M.S. Carr et. al., "Iron in the United States," *Minerals Investigation Resource:* MR-51 (1967).

33/ W.F. Prudeb, "Taconite - New Iron Ore for the West as U.S. Steel Builds at Atlantic City," *Mining World* (March, 1961), pp. 18-21.

34/ A.M. Bateman, *Economic Mineral Deposits,* New York: John Wiley and Sons (1950), pp. 536-538.

35/ C.A. Anderson and S.C. Creasy, *Geology and Ore Deposits of the Jerome Area, Yavapai County, Arizona,* U.S. Geological Survey Professional Paper 308 (1958), p. 2.

36/ A.M. Bateman, *op. cit.,* p. 424.

37/ C. Dunbar, *op. cit.,* pp. 99-100.

38/ A. Long et al., "Isotopic Composition of Lead and Precambrian Mineralization of the Coeur d'Alene District, Idaho," *Economic Geology,* Vol. 55 (1960), pp. 645-658.

39/ J. Gilluly, "Volcanism, Tectonism, and Plutonism in Western United States," Geological Society of America Sp. Paper 80 (1965), pp. 21-22.

40/ D.L. Kendall, "Ore Deposits and Sedimentary Features, Jefferson City Mine, Tennessee," *Economic Geology,* Vol. 55 (1960), pp. 985-1003.

41/ C. Dunbar, *op. cit.,* pp. 203-205.

42/ P.F. Howard, "Structure and Rock Alteration at the Elizabeth Mine, Vermont," *Economic Geology,* Vol. 54, pp. 1214-1249.

43/ M.S. Carr et al., *op. cit.,* p. 2.

44/ C. Dunbar, *op. cit.,* pp. 285-287.

45/ J. Gilluly, "Tectonic Evolution of Western United States," *Quarterly Journal,* Geological Society of London, Vol. 119, pp. 138-142.

46/ *Ibid.,* pp. 144-145.

47/ J. Gilluly (1965), *op. cit.,* pp. 15-16.

48/ E. Wisser, "Cordilleran Ore Districts in Relation to Regional Structure," *Canadian Mining and Metallurgical Bulletin,* Vol. 52 (Jan. 1959), p. 8.

49/ C. Dunbar, *op. cit.,* p. 316.

50/ *Ibid.,* p. 404.

51/ H.E. McKinstry, *Mining Geology,* New York: Prentice-Hall, Inc. (1948), p. 206.

CHAPTER 4

THE MINERAL RESOURCES OF THE UNITED STATES

Have fundamental differences appeared in the major characteristics of non-fuel minerals deposits that have been brought into production in the United States since 1947?

Have these deposits differed substantially from those in production prior to 1872?

A. KNOWN MINERAL RESOURCES BEFORE 1872

1. Early Gold Deposits

Only a hundred years ago the vast territory between the east front of the Rocky Mountains and the Pacific was largely unexplored. Tribes of hostile Indians roamed at will over large areas. There were almost no railroads, the first transcontinental line not being completed until 1869. Transportation was by horse, wagon, or foot.

The California gold rush, beginning in 1848, was directly responsible for starting the amazingly rapid settlement and exploitation of the vast areas along the Pacific Coast of the United States.

> "The discovery of gold in California by Marshall in 1848 was the most portentous event in the history of modern mining because it gave an immediate stimulus to world-wide migration; it induced an enormous expansion of international trade; and it caused scientific industry to invade the waste places of the earth. It is true, the occurrence of gold in California was known previously, but the finding of gold and the knowledge that it could be found were by themselves of little moment; it was the production of gold on an industrial scale, and lavishly, that rendered Marshall's fortuitous discovery so momentous."[52]

In January, 1848, James Marshall discovered gold in the tail-race of a sawmill he was building on the south fork of the American River, 40 miles northeast of what is now Sacramento, California. Marshall was in partnership with John Sutter, a Swiss merchant-adventurer who had obtained title to a vast block of ground in the Sacramento Valley. Fearing the event that soon ruined him, and the loss of his land to vast hordes of squatters, Sutter tried to quiet news of the discovery but word got around. The gold find was announced in a San Francisco paper, and the rush was on.

In 1848 California was still under military rule. Although the gulches in the Sierra Nevada foothills swarmed with miners, the officer in command in 1848 thought it best not to interfere with them. His successor in 1849, General P. F. Smith, thought likewise. He pointed out that the mines were on public land that belonged to the government, but that it was not desirable to have the mines worked for the benefit of the public treasury. According to General Smith, "To do that would require an army of officers and inferior agents, all with high salaries, and with opportunities and temptations for corruption too strong for ordinary human nature."[53]

As a result, the miners were left to their own resources although clearly something had to be done to protect individual diggings and avoid anarchy. Mexican mining law was no longer operative in California; no United States law was applicable to the situation; and there was no state government as yet. The miners, therefore, drafted their own regulations, and their local rules became the substance of the United States mining law passed in 1866. The basic idea involved the right to locate a mining claim and to hold it by continuity of work.[54]

The California gold placers lay in gulches, in the western foothills of the Sierra Nevada,

Preceding page blank

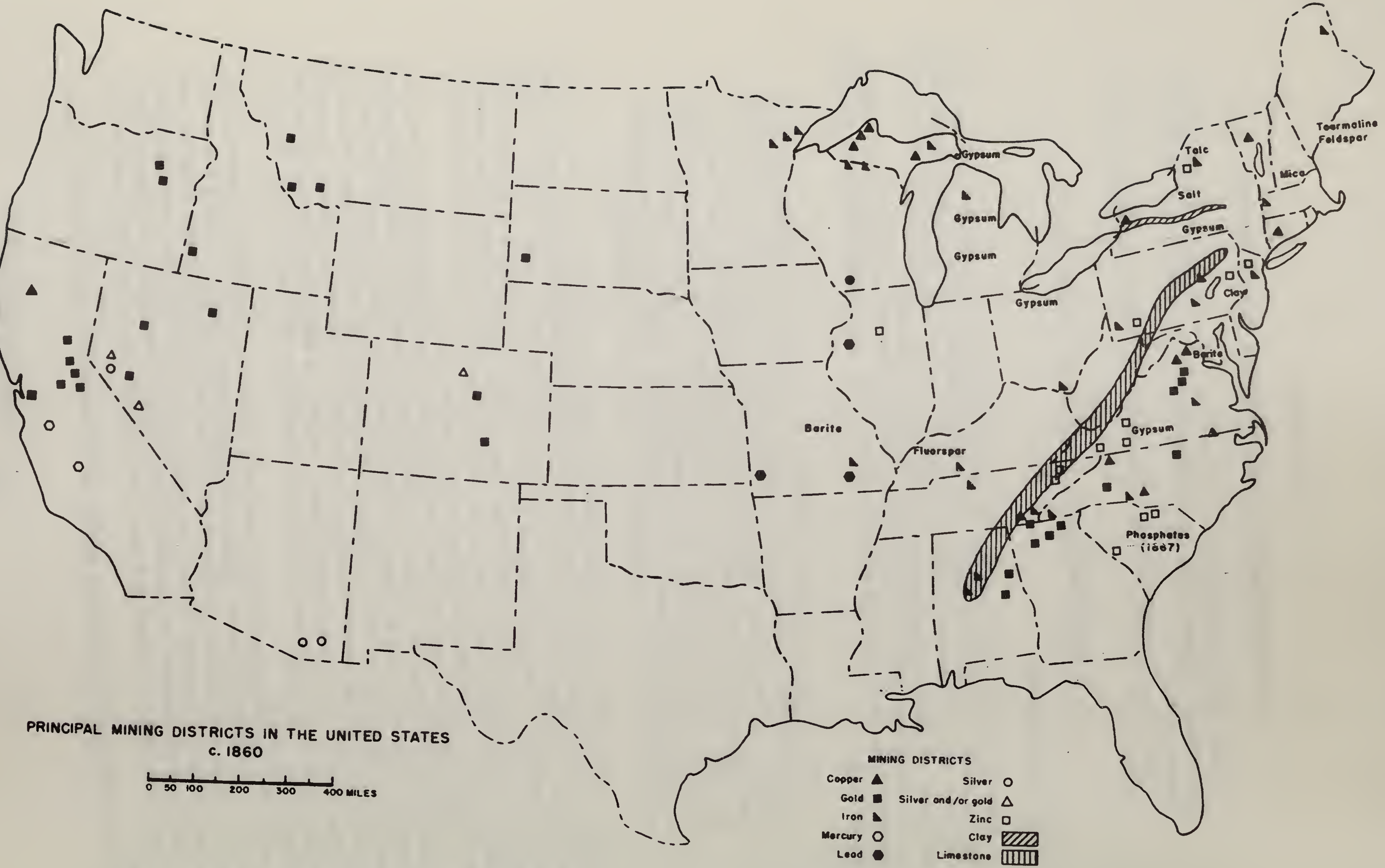


Fig. 26 - The major known mineral resources of the United States prior to enactment of the mining laws of the late 1860's and 1872. At that time, nearly all United States mineral industry

below the outcrops of one of the greatest belts of gold veins in the world, the Mother Lode. This system of veins extends in the high western foothills of the Sierra for over 100 miles, running roughly north and south. A few miles north of the Mother Lode lies Grass Valley, a highly productive gold district, with narrower but richer veins. Discovery of these vein outcrops quickly followed the placer mining that had proceeded eastward toward the outcrops. Between 1850 and 1852 most of these gold-bearing veins had been found.[55] With their discovery, vein or lode mining began to supplant the earlier placers. Lode mining, involving solid rock instead of loose gravel, was vastly more expensive than placer mining, and technically much more difficult. It is not surprising, therefore, that placer gold production continued to exceed that from lodes (veins) until 1873.[56]

The finding of placer gold in California was the prelude to an intensive search for other placers over the entire Pacific slope. As one mining historian has noted, "Alluvial gold is the best mineral for pioneer mining, because it is extracted by simple methods, and, on account of small bulk in proportion to high value, is cheaply transported. The first discovery of gold, therefore, is an important event in the history of any region."[57] Since thousands of dollars worth of gold may be carried by a single pack-mule, any immediate need for sophisticated transportation facilities is postponed.

In 1849 a party of Georgians, on their way to California with a herd of horses to sell to the placer miners, camped on Cherry Creek near the present site of Denver, Colorado. Panning the creek bed, they found gold. They found even more, 16 miles further upstream in the higher foothills of the Front Range. In 1850, however, they moved on to California where they placer mined. They returned to Georgia in 1857, but resolved to investigate the Colorado showings further. In 1858 they returned to their old camp on Cherry Creek and prospected even further upstream, finding more and more placer gold.[58]

The word of the Colorado discovery spread and a gold rush ensued, resulting in the discovery in 1859 of the Gregory Lode at Central City, Colorado, the first gold lode discovery in Colorado. In the same year other lodes were discovered, all lying within the so-called "mineral belt," which extends southwest-northeast across the Front Range of the Colorado Rockies. The belt persists southwest of the Front Range and contains such major mining districts as Leadville, Aspen, and the San Juan district. To this day it has produced an overwhelming proportion of Colorado's metal yield.

It is not surprising that gold placers were found near gold-bearing veins, because weathering tends to liberate the gold from the rock, and surface water transports it down hill and deposits it with gravel. What may be surprising is the fact that gold placers were also found near deposits of lead and zinc sulfides containing high silver but relatively little gold. The explanation lies in weathering, with its oxidation and solution of host rock and less resistant minerals. Pyrite, the iron sulfide which accompanies most metallic mineral deposits, is altered by weathering to iron oxide, resulting in a liberation of iron sulfates and sulfuric acid. These chemicals are able to dissolve many other vein minerals such as calcite and zinc sulfide. Gold resists oxidation, however, and remains in the outcrop, which is thus enriched by the mere decrease in the volume of other constituents. As the remaining gold is washed off the hillside by surface water, it is further concentrated by reason of its great weight, dropping out of the stream flow and percolating through the gravel toward bedrock where the stream loses its velocity, while the finer gravel and sand continue downstream.[59]

An example of the result of this process were the deposits at Leadville, Colorado, 80 miles west-southwest of Denver. The unoxidized mineral deposit contained sulfides of lead, zinc, and iron with substantial silver but very little gold replacing limestone. In 1860 gold was found in stream sands near Leadville. The immediate result was extensive placer mining which lasted 15 years. It was not until about 1875, however, that the first oxidized lead outcrop was discovered.[60]

In 1861, after a treaty had been signed with previously hostile Indians, Idaho swarmed with gold prospectors—an estimated 5,000 in that year, 20,000 during the next summer, and 25,000 in 1863. In June of 1861, the gold-bearing quartz veins of Silver City in Southwest Idaho were discovered.

Of the states outside of California, Montana was by far the richest in placer gold deposits. In 1862 placers discovered at Bannack, Montana, (60 miles southwest of Butte), became the scene of the first important mining operation in the state. Outcrops of gold veins were found there the same year. In 1863 the far larger and richer placers in Alder Gulch were found about 60 miles south-southeast of Butte. By 1868, $30 million in gold had been won from these placers. Placer mining led directly to the discovery of the gold vein district of Virginia City, Montana, nine miles to the north of Alder Gulch. The Silver Bow placers in the valley below Butte Hill were discovered in 1864. By 1867 they had been almost abandoned, but their discovery led indirectly to the development of the fabulous copper deposits at Butte. In 1865 rich gold placers were discovered on the site of what is now Helena, Montana, in what shortly became a highly productive gold vein mining district.

> "In Montana, as elsewhere, the placer miner blazed the trail for the lode miner; indeed, widening the generalization, one may say that all over our western domain, as in other parts of the world, the finding of gold has been the first step in the development of a mining industry."[61]

In 1864 Californians returning from the placer diggings of Montana to spend the winter in the Salt Lake Valley found gold in Bingham Canyon, 20 miles southwest of Salt Lake City, thus directing attention to what later became one of the great copper mining districts of the world. In the same year, fragments of silver-bearing, oxidized lead minerals were found.[62]

2. Early Silver Deposits

Silver, because of its lighter weight than gold and its tendency during weathering to be dissolved and removed in solution, does not lend itself to the formation of placer deposits. Furthermore, silver, unlike gold, occurs only rarely in its native state, and special geologic knowledge is required to recognize silver minerals whereas gold can be easily recognized by even the novice prospector. It was the discovery of the great Comstock Lode, a few miles south of Reno, Nevada, that brought to western prospectors a more specialized knowledge of silver deposits.

There had been minor gold placers mining in the vicinity of the Comstock Lode from 1849 to 1857. In 1859, two placer miners found all of the lower ground already staked, so they moved up the slope of Mount Davidson, toward the outcrop of the lode which was then still unknown. There they found gold specks in loose dirt. Digging a small basin to conserve the scanty water from a spring for placer mining, they uncovered sandy material and quartz, with fragments of black rock, some of which was the black silver sulfide, argentite. A reportedly disreputable character named Henry Comstock came along, asserted they were on his ground, and bluffed them into accepting him as partner. On June 8, 1859, they staked claims for 1,500 feet along the lode. At the end of June, a rancher carried a piece of the black rock to Grass Valley, California, where it was assayed. It contained $3,000 worth of silver to the ton. A man named Walsh, who had the piece assayed, and the assayer started hell-bent for the Comstock Lode and bought out the partners for a trifling sum. Their claims became the Ophir Mine, which eventually produced nearly $18 million in silver.[63]

The price of silver stayed at $1.30 per ounce, or more, until 1872, and remained above $1.00 until 1893, when it was demonetized, to the indignation of William Jennings Bryan and others. The price then dropped abruptly and has risen only in recent years.

The Comstock Lode was a silver-gold vein, with little lead or zinc. Similar veins were fairly abundant in the West in the 1860's, in Colorado, Idaho and elsewhere, but more important sources of silver over the years have been the silver-lead-zinc deposits with low amounts of gold. Such deposits occur in the Coeur d'Alene district in Northern Idaho, where these occur in wide vein-like lodes in quartzite. Usually, however, they form irregular masses in limestone, as at Eureka, Nevada, at Tintic and Park City, Utah, and in numerous districts in Northern Mexico. Such mineral deposits carry their metals as sulfides below the zone of weathering, and the silver content there is relatively low. The sulfide minerals at Eureka, Nevada, for example, where the zone of weathering had an extremely high silver content, carried eight ounces of silver per ton.

In the zone of weathering (between the top of the sulfide mineral zone and the surface), sulfur, zinc, and other elements are mostly removed by acid solutions derived from the oxidation of sulfides, mainly iron pyrite. Lead sulfide in limestone deposits is altered to lead carbonate. The silver typically remains with the lead carbonate, usually as a silver chloride. The silver content of these lead carbonate mineral deposits has been fabulously high. Some of the high content was due to residual enrichment, i.e., the removal of valueless material during weathering. But the remarkably high silver content in oxidized lead ores nearest the surface at Leadville suggested to at least one geologist that the silver was in part concentrated and transported downward as the outcrops of the ore bodies were lowered by erosion.[64]

The Gadsden Purchase of 1854 brought into the United States a strip of land that had been part of Sonora, Mexico. There the Spanish tradition for silver mining had been in existence for several hundred years. Probably guided by Mexicans, Americans discovered and brought into production a number of silver mines in Southern Arizona in the 1850's, even before the discovery of the Comstock Lode in Western Nevada. The discovery of the Comstock in 1859 stimulated strong interest in silver throughout the Western United States. The Comstock Lode carried silver as a sulfide, however, and presented metallurgical difficulties.

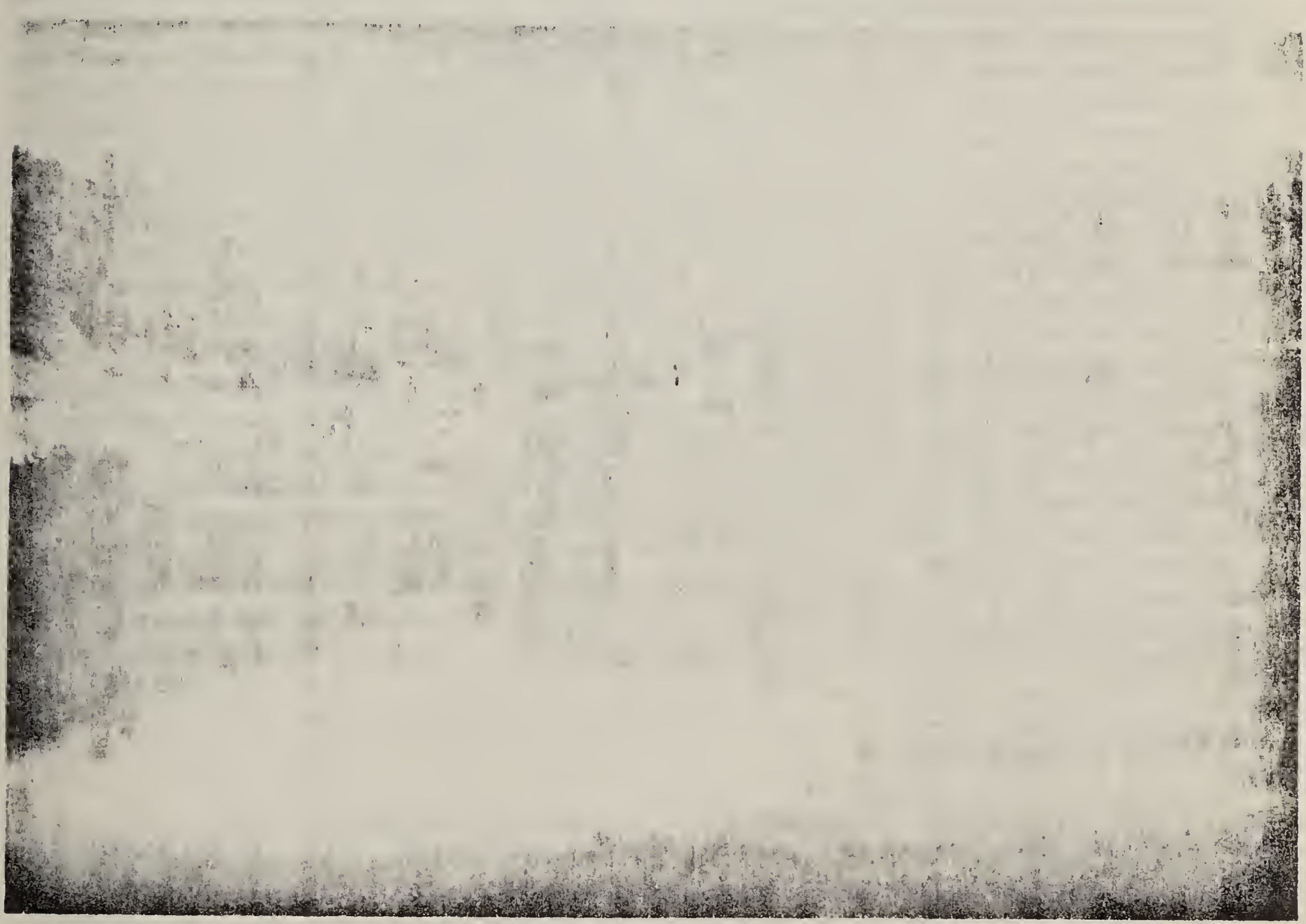


Fig. 28 - Inoperative gold dredge on a stream south of Helena, Montana, in an area rich in gold placer deposits in the 1860's. Early placer mining here led to later discoveries of silver and copper deposits that subsequently were mainly responsible for the settlement and economic development of Montana.

3. Early Lead Deposits

Lead carbonate deposits often carry high concentrations of silver and are more easily smelted than the silver sulfides. Among such silver-bearing lead carbonate deposits, those at Eureka and White Pine, Nevada, came into production in 1869. Those at Cottonwood, Utah, began producing in 1870, while those at Pioche, Nevada, and Park City, Utah, started in 1872. At Leadville, Colorado, production from similar deposits started in 1875. Silver sulfide deposits at Tombstone, Arizona, were not developed until nearly 1880.

The smelting of oxidized lead ores has been known for thousands of years. The ancient Romans used lead water pipes. In the American west, some smelting of lead carbonate ores for local, domestic purposes was done in early years. Thus, in 1856 Brigham Young sent Mormon prospectors out from Salt Lake City in search of needed lead. One of them found what later became the Goodsprings silver-lead-zinc deposits near Las Vegas, Nevada. He smelted about four tons of lead but, in general, the attempt at persistent production was a failure.[65]

A year before, in 1855, the Mowry lead carbonate deposit, northeast of Nogales, Arizona, was purchased by army officers. In 1858 a Lieutenant Mowry obtained sole control. This was the first lead-silver mine west of the Rockies to be operated on a fairly important scale. Rumor has it that the lead was used to make bullets for the Confederate Army after the Civil War broke out. This seems confirmed by the fact that in 1862 Federal troops, who had chased the Confederates out of Arizona, destroyed the mine plant.[66]

The first lead carbonate deposits to be brought into production on a really large scale in the West were those of Eureka, Nevada, 90 miles south of Elko. Outcrops of silver-bearing lead carbonate ore were discovered there in 1864. Large quantities of ore were exposed, but they excited little interest. The ore was unfamiliar to the prospectors, bearing no resemblance to the Comstock silver ore, and lead smelting on a commercial scale was unknown in the West. This was still before the coming of the railroads, which were needed to provide the cheap transportation that is a necessary adjunct to the base metal industry.

Mining started at Eureka in 1869, however, and by 1870 a satisfactory smelting method was devised. This had an important effect on the exploitation of other important lead carbonate deposits, because the method was applicable to all of them.[67] To date, Eureka has produced over 60 million ounces of silver plus abundant lead. Major production ended in 1885, but some production persisted through 1929.[68]

In 1865 a lead smelter was erected at Argenta, Montana, marking the beginning of large-scale lead smelting in the West. In 1866 the Selby smelter was built in San Francisco and was later moved to its present location on tidewater to the north. In 1869 the Central Pacific Railroad coming east joined up with the Union Pacific advancing west to complete the first transcontinental rail connection. This transcontinental link along with branch lines and other main railroads gave a great impetus to the base-metal industry in the West.

The first claim located at Tintic, Utah, was staked in 1869 on a deposit of lead carbonate rich in silver. Development was slow for the first few years because of the difficulty involved in getting the ore to market. In 1878, however, the Utah Southern Railroad was extended to the Tintic area, and in the following year production nearly doubled.[69]

4. Early Copper Deposits

The copper deposits of the foothills copper-zinc belt in California were discovered in 1861 and copper was mined on a small scale at Silver Bell, Arizona, starting in 1865. For the most part, however, copper production in the West had to await the coming of the railroads. Copper production began at Morenci, Arizona, in 1881; at Butte, Montana, in 1882; at Bisbee, Arizona, in 1885; at Jerome, Arizona, in 1888; and at Bingham, Utah, in 1897. Prior to 1872, virtually all of the nation's copper was produced in the Lake Superior district of Northern Michigan.

5. Other Early Mineral Deposits

In 1860 the California gold placers in the western foothills of the Sierra Nevada (which had been discovered in 1848) were still producing heavily. Most of the quartz veins of the great Mother Lode, the belt of gold veins which traverses the western foothills of the Sierra Nevada for over 100 miles, had been discovered, but in 1860 were just coming into production. The quartz veins of the Weaverville district in Northern California, however, had been discovered in 1852 and were in full production by 1860.[70] By that time, also, placer and lode gold were being produced in the Taylorsville area, north of Lake Tahoe near the crest of the Sierra.[71]

The New Almaden mercury mine, south of San Francisco, had been in production since 1850, and the New Idria mercury mine, farther south, since 1858.[72] The mercury produced by these mines was of extreme importance to the gold miners. The ability of mercury to pick up flakes of gold and amalgamate (absorb) the gold was utilized by both placer and vein miners prior to 1872 and in fact has been used in many places up to relatively recent times.

Production of industrial minerals was limited and local in the West prior to 1872. Coal was being mined locally for fuel. Clay was quarried for the making of common red brick, while limestone was burnt to make quicklime for plaster, mortar, and whitewash.

6. Early Mineral Deposit Characteristics

Mineral deposits known to exist prior to 1872 both in the eastern and western portions of the country possessed many common characteristics. Most were relatively small deposits, at least the known and economically workable portions were small. They covered relatively small areas, measured in hundreds of feet both on the surface and in depth. Total tonnages of known reserves were measured in tens of thousands of tons.

Even though most producing deposits were small, it should be noted that many were simply relatively small high-grade portions of much larger mineral deposits which did not become known or considered as valuable mineral deposits until the 20th Century.

Most *known* mineral deposits in the United States in the 1860's were relatively close to the surface and, in fact, had been discovered as outcrops or surface deposits of alluvial material. Concealment, where there was any, was provided only by vegetation and soil or relatively thin beds of surface gravel or *talus*. These did not include, of course, the mineral deposits, concealed at depth that were then in existence (and subsequently worked) adjacent to known deposits that were exposed at the surface. In the West such concealment at depth was limited almost exclusively to metallic minerals, particularly gold, silver, mercury, and lead, which tended to occur in *ore shoots*, or zones of higher concentration, even within a given mineral deposit. Such ore shoots were often elusive targets for the early miner even when he had found the vein.

Most known metallic mineral deposits in the United States prior to 1872 (except for gold placers) were in veins or vein-like structures. Some massive replacement deposits were known and lens or pod deposits were also being worked. Except for gold (and copper in Michigan) which occurred as native metal, most metallic ore minerals were carbonates or oxides, products of surface geologic conditions and chemical processes. Sulfides were not widely considered to be ore minerals except in the cases of silver and mercury. The most common gangue minerals were the quartz and calcite which comprised the groundmass of the veins in which the ore minerals were usually found.

Before 1872, as now, valuable mineral deposits were found in a variety of geological environments. But the most common involved intrusive igneous, metamorphic, and limestone host rocks. Deposits of metallic minerals were perhaps most commonly known to occur in heavily metamorphosed areas around the edges of large igneous intrusions (e.g., the Sierra Nevada Batholith) or in folded and faulted limestones where mineralogical replacement had taken place. In the eastern part of the nation this was also true, with deposits in the Canadian Shield and Appalachians being those that dominated.

The non-metallic minerals, principally salt, calcium carbonates, and clays were extracted from surface deposits that were known to be widespread throughout the United States at this time. Except for certain clays considered particularly valuable for special grades of pottery, there was little distinction between deposits of roughly equivalent materials. Virtually all industrial minerals were used as extracted with no additional processing except for the burning of limestone to produce lime.

Many of the mineral commodities now produced commercially in the Western United States were not even considered to be in existence prior to 1872. For many of them there simply was no commercial use. Among the metals, aluminum, for example, was not brought into industrial use until after the invention of the Hall Process in the early 1900's. Among the other metals, even zinc was not being mined commercially in the United States in the 1860's, nor were nickel, vanadium, manganese, tungsten, molybdenum, or beryllium. Uranium, of course, did not come into prominence as a non-metallic mineral resource until almost a century later. As shown in Table 6, only a relative few of the minerals now widely used in American industry were produced domestically before 1872.

Of those metals that were being mined commercially in the United States in the 1860's, iron ore deposits commonly contained about 60 percent iron as iron oxide. These were direct reduction ores, as there was virtually no ore beneficiation practiced at that time. Copper deposits, where commercially useable in the West, contained from five to six percent copper in oxide or carbonate form. These also were direct smelting ores. Only in the upper Michigan native copper district did commercially useable copper ores in the 1860's contain as little as two percent copper. Lead ores that were mined in the United States prior to 1872 averaged about 25 percent lead. Mercury had been mined in the West for a number of years by 1860 and the quicksilver content of the ore deposits then used ranged from one to two percent mercury occurring as cinnabar.

Even the precious metals in the 1860's were minable in most places only from much higher grade ore bodies than at present. Economically workable gold deposits (except in the Mother Lode) contained from one to two ounces per ton. Commercially useable silver ores ranged from 40 to 90 ounces per ton.

Of the numerous non-metallic minerals presently mined in the United States prior to 1872, only calcium in its carbonate form as limestone and sodium in its chloride form as salt were of substantial commercial importance. Calcium carbonate deposits at that time contained about 40 percent calcium. This is roughly equivalent to between 90 and 95 percent calcium carbonate in the naturally occurring limestone. Deposits of sodium chloride that were commercially workable in the 1860's contained about 40 percent sodium, or better than 90 percent pure sodium chloride. Other non-metallics, such as potash, phosphates, and sulfur were not mined at all commercially in the United States before 1872.

Table 6

MINIMUM CONCENTRATIONS OF SELECTED ELEMENTS NORMALLY NEEDED FOR ECONOMIC MINERAL DEVELOPMENT IN 1860

Element	Minimum Necessary Recoverable Content (in parts per million by weight)		Grade (Percent)	Weight Content (lbs/ton)
Aluminum	NSM		–	–
Iron	600,000		60	1200
Calcium	400,000	(in carbonate form)	40	800
Sodium	390,000	(in chloride form)	39	780
Potassium	NSM		–	–
Phosphorus	NSM		–	–
Manganese	NSM		–	–
Sulfur	NSM		–	–
Vanadium	NSM		–	–
Nickel	NSM		–	–
Zinc	NSM		–	–
Copper	50,000	to 60,000	5 to 6	100 to 120
Lead	250,000		25	500
Beryllium	NSM		–	–
Uranium	NSM		–	–
Tungsten	NSM		–	–
Molybdenum	NSM		–	–
Mercury	20,000	to 10,000	1 to 2	20 to 40
Silver	1,400	to 3,100	.14 to .31	34 to 74 oz/ton
Gold	30	to 70	–	0.7 to 1.7 oz/ton

NSM - No significant mining in the United States

Sources of data: Various

B. CHANGES IN MINERAL RESOURCES TO 1947

1. Changes in Mineral Deposit Characteristics

The small bonanza ore bodies which were found and mined between 1860 and 1900 in the Western United States were largely secondary, enriched deposits of the precious metals, copper, and lead. When the deeper primary zone was reached in these deposits, mining stopped, in most cases due to the lower grade of rock. As technology advanced and demand increased, ways were found to mine the lower grade rock at a profit and many mines were reopened. In a number of mining districts, large areas containing low-grade rock, previously ignored, were made into profitable mines. Since 1860 the mining industry in the Western United States has progressed from small, rich ore deposits to progressively larger and lower grade mineral deposits which were made into mines by a combination of more advanced technology and/or increasing prices and demand for the product.

By the end of World War II, the grade of commercially workable mineral deposits in the United States had declined considerably from the levels existant prior to 1872. The average grade of commercially useable gold ore in place had gone from two ounces per ton down to 22 hundredths of an ounce per ton. Placer gold, to be commercially workable, needed only 48 ten thousandths of an ounce of gold per ton. Silver ore averaged a little under 20 ounces per ton.

The changing technologies of metal mining over the more than 80 year span from 1860 to 1947 also had their impact upon the grade of commercially useable base metal deposits. The beginning of large scale mining (both open-pit and underground block caving) methods in the early 1900's had reduced the average content of copper ores from about five percent in 1860 to less than one percent by 1947. Lead ores had dropped from 25 percent to one-tenth that amount, and ores of less than three percent lead were being mined commercially in the United States in the late 1940's. Zinc, in many instances a companion product with lead, by 1947 was being mined where it had not been mined at all prior to 1872. In 1947, the average grade of zinc ores mined in the United States was about five percent zinc.

Advanced and cheaper minerals beneficiation techniques also had their impact on iron resources. From ores containing about 60 percent iron in the 1860's, the average grade of iron ore mined in the United States had dropped to about 40 percent iron by 1947, and most of this required beneficiation of one kind or another before being suitable as blast furnace input.

Mercury ores mined in the United States had also declined in average grade by 1947. In that year, ores averaging about 12 pounds per ton or six-tenths of one percent mercury were being mined in California and other parts of the West. This was about one-third of the two percent ores mined prior to 1872.

By the end of World War II, other metals were being mined for the first time in the United States. In 1947, molybdenum was being mined in the United States as a steel-alloying metal and the average grade of its ores was about three-tenths of one percent molybdenum. Uranium had just begun to be mined. The average grade of uranium ore was running about two-tenths of one percent U_3O_8. Nickel, another major metal in the alloying of steel, was still not being mined in the United States in 1947, and virtually all of the nation's needs were supplied from Canada.

Among the industrial minerals the average grade of limestone and sodium chloride deposits in 1947 remained practically unchanged from the average grade mined in the 1860's. Among some of the newer industrial minerals, however, phosphates had come into wide use by 1947. In that year, rock containing 12 percent P_2O_5 was being mined commercially in the United States.

2. Changes in the Location of Mineral Resources[1]

Most of the changes that took place in the known mineral resources of the United States between the 1860's and the end of World War II reflected the general westward movement of the nation's population and industry. The discovery and development of mineral resources west of the Mississippi is virtually the story of the taming of the West.

In 1875, as placer gold mining was dying out at Leadville, Colorado, a prospector recognized lead carbonate ore. Knowing it probably carried silver, he sank a pit on an outcrop of low-grade ore. This stimulated the search for similar deposits in the area, so that by 1878 the output of silver-lead ore at Leadville totalled $3 million.[73] The first smelter in the area was constructed in 1878, and it was shortly followed by a number of others. The rich yield in silver from Leadville ores led to the discoveries at Aspen, Colorado, of similar lead-silver deposits in 1880.[74] Aspen lies just 30 miles west of Leadville.

In 1874 a rush of miners invaded the San Juan region in Southwestern Colorado. Despite the fact that machinery had to be packed in on burros from Colorado Springs, then the terminus of the Denver and Rio Grande railroad, a smelter was erected north of Silverton. The lead-bearing mineral deposits there lay in veins and were not limestone replacements as at Tintic and Leadville. But they were rich in silver, and they still produce lead and zinc. Between 1873 and 1928 the San Juan region produced more than six million ounces of gold, 128 million ounces of silver and abundant lead and zinc.[75]

The great Homestake gold mine in the Black Hills of South Dakota must be mentioned as a part of western mineral resources. The outcrop of an irregular body of gold ore in schist was discovered and staked at Homestake in 1876.[76] The mine is at present the largest producer of gold in the United States. The great gold camp of Cripple Creek, Colorado, west of Colorado Springs, was discovered in 1891. There, gold occurred in narrow veins associated with tellurium.[77]

In 1877 the silver-lead-zinc deposits of Tombstone in Southeast Arizona were discovered. In 1879 the Southern Pacific had reached Casa Grande near Phoenix and by 1880 had reached Benson, only 30 miles from Tombstone. With the coming of the railroad, the bringing in of supplies and the shipment out of ore were greatly facilitated and Tombstone became a major site of silver reserves.[78]

Attention was first drawn to the Coeur d'Alene silver-lead-zinc lode deposits in Northern Idaho by the search for gold placers. In 1885, the tracing of a piece of galena float up a hill led to the discovery of the great Bunker Hill Lode. This great district has been operative, with only a few shut-downs due to labor strikes and low metal prices, ever since. Once ores rich in silver near the surface had been exhausted in early years, the value of base metals produced in the Coeur d'Alene equalled or perhaps exceeded that of silver, at least up to 1931. But in 1931 rich silver-copper ore was discovered on the 1700 foot level of the Sunshine Mine.[79] In this way the famous Coeur d'Alene "Silver Belt" was discovered. The Coeur d'Alene district is today the largest producer of silver in the United States.

In 1900 came the discovery of the silver district of Tonopah, Nevada, 180 miles southwest of Reno, and in 1906 that of the gold camp of Goldfield, 25 miles south of Tonopah. Base metals are sparse in both districts.[80]

Although a number of small districts were developed (see Figure 29), there were no gold, silver, or lead districts of any major importance discovered in the West between 1906 and 1946. In 1942 wartime restrictions forbade the mining of gold except as a by-product in the production of critical war metals. In 1945 the ban on gold was lifted, but because of increased costs and the expense of rehabilitating abandoned mines, there was little revival. In 1947, few straight gold mines besides Homestake were operating in the United States.

It has been suggested that there were shifts in the location of the principal known resources of gold, silver, and lead in the West between 1872 and 1947. The astonishing fact, however, is the relative lack of such shifts since the discovery of the Coeur d'Alene district in 1885. The only major districts brought in between that year and 1946 were Cripple Creek (1891), Tonopah (1900), and Goldfield (1906). Such present-day producers as Bingham,

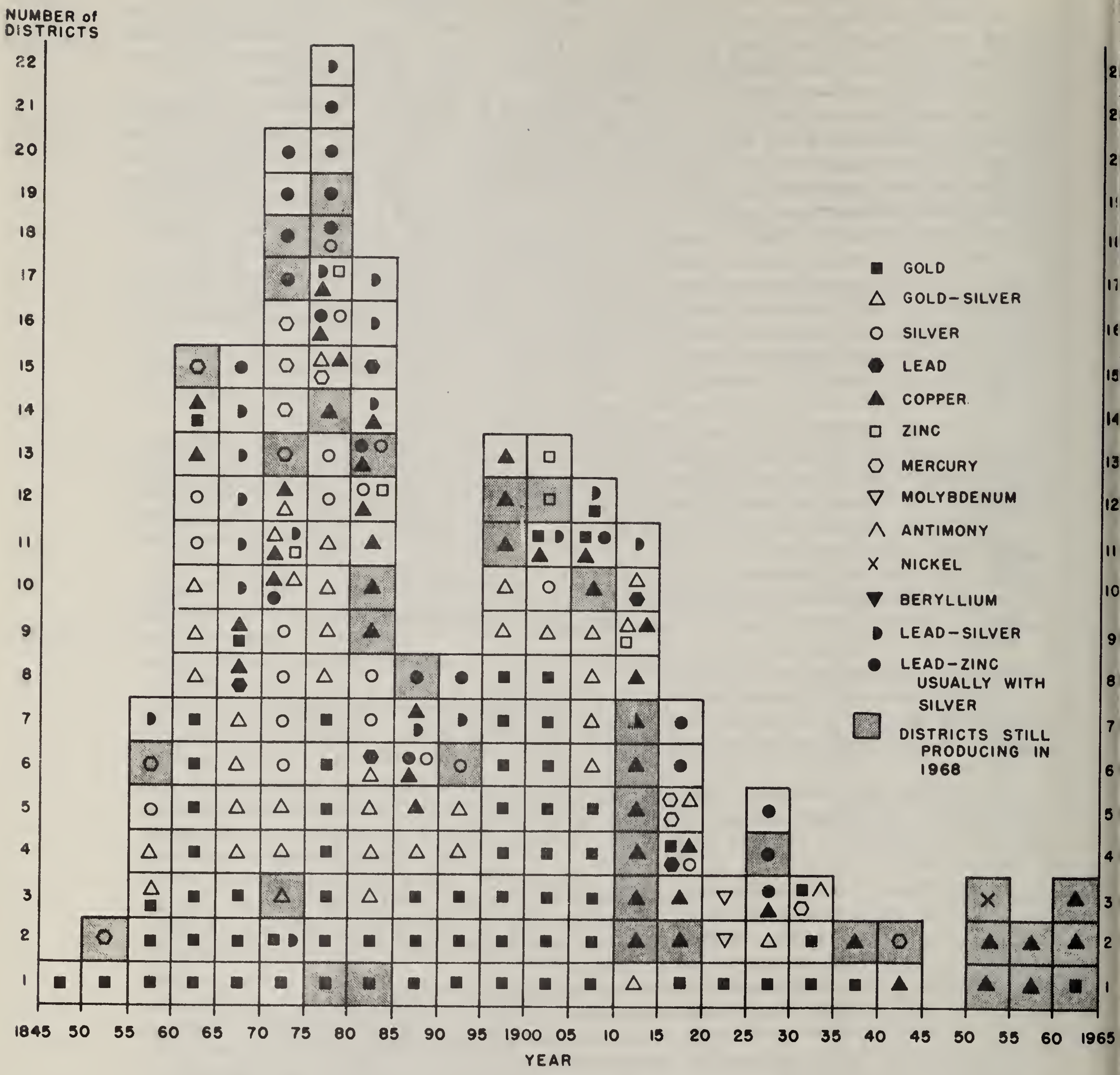


Fig. 29 - Metal mining districts brought into production in the Western United States from 1845 to 1965. Most of the new development occurred between 1860 and 1920. In the 1870's, the decade which saw the greatest development, more than 40 new mining districts were brought into production. At least eight of these still provide metallic minerals for the nation's industry.

Butte, Park City, and Tintic have been known for 90 years or more, although the first production from some of these did not start that early. There have been important gold discoveries since 1946, but none of any major silver-lead districts. Have they all been found? The answer is safely no, but the finding of new resources may depend on advances in exploration techniques not presently in sight.

From 1860 to 1882 the Lake Superior region of Northern Michigan accounted for between 95 and 63 percent of total United States copper production, depending on the year.[81] As mines in the Western United States were developed, the Lake Superior region's share of total domestic copper production fell. Beginning about 1880,[82] Arizona and Montana became important copper producers. By 1900 Lake Superior production had dropped to less than a quarter of the total, while the Butte, Montana, district had become the largest single producing area with nearly 45 percent of the total.[83] Arizona occupied third place with almost 20 percent of the total. Michigan, Arizona, and Montana combined accounted for nearly 90 percent of total copper production in the United States in 1900.

In the first part of the 20th Century, the shift in production toward the West continued. By 1910 Butte's share had decreased, while Arizona's had increased. By 1915 the Lake Superior region's share had fallen to less than a sixth, and nine western districts (in Arizona, Montana, Utah, Nevada, and New Mexico) accounted for almost two-thirds of domestic copper production.[84] Five districts in Arizona (Bisbee, Globe, Ray, Jerome, and Morenci) produced nearly 30 percent, making that state the nation's leading site of copper resources. These major districts, along with newer ones and small mine production from other districts, have made Arizona the leading domestic copper producer from 1910 to date.[85]

The discovery and development of copper mineral deposits in the United States since 1872 have fallen into two main periods, with some overlap. The first involved the mining of high-grade deposits, veins, massive replacements in limestone, and other similar types of ore deposits. The second entailed the mining of large, very low-grade "porphyry coppers" such as those at Bingham, Utah, and Morenci, Arizona. Phase two only came into being after the first porphyry copper, Bingham, had been successfully put into production by the Utah Copper Company in 1907.

In the first phase at Morenci, in far eastern Arizona, high-grade carbonates and oxides of copper were mined before 1880 and smelted locally. Carbonate and oxide copper minerals

Table 7

LEADING COPPER PRODUCING DISTRICTS IN THE UNITED STATES, 1910

District	Percent of Total Domestic Production
Butte, Montana	26.2
Lake Superior	20.5
Bisbee, Arizona	13.2
Bingham, Utah	10.4
Morenci, Arizona	6.8
Ely, Nevada	5.8
Jerome, Arizona	3.6
Shasta, California	3.3
Globe, Arizona	2.6

Source of Data: *Mineral Resources of the United States, Part I, Metals, 1910,* U.S. Geological Survey, p. 165.

are relatively easy to smelt. The *matte* (crude copper metal plus some impurities that had to be refined out) was hauled by wagon from the Morenci district 1200 miles to Kansas City. These high-grade oxide ores, averaging 20 percent copper, occurred in limestone. The great bulk of more recent Morenci production, however, has come from relatively low-grade, disseminated copper minerals in an intrusive rock allied to granite.

Although the Bingham pit is considered the pioneer and prototype of the low-grade, large-scale "porphyry" coppers, Morenci in a sense foreshadowed it. In 1900, when the carbonate-oxide ores in limestone at Morenci were nearly depleted, the low-grade sulfides in the porphyry were explored. By 1904 the Humboldt porphyry copper mine was one of the Morenci district's main producers. The grade of ore ran from three to four percent copper, considerably higher than that of the typical porphyry copper in operation today. Mining of the vast Morenci porphyry ore body, carrying one percent copper, did not come until much later, however.[86]

Butte, Montana, was the first major copper vein district to be exploited in the United States. It is by far the greatest still. As has been mentioned, gold placers first directed attention to the Butte area. The transition from gold mining to copper mining was by way of silver mining. This was natural when one reflects that silver in the late 1860's (after the strong rise in copper price owing to the Civil War) and in the 1870's (except for a brief rise in price, 1872-73) was worth about six times as much per ounce as copper was per pound.

The first lode claim was staked on the hillsides of Butte in 1864, and was soon followed by others. The claim-stakers were looking for freemilling gold ore (i.e., gold that could be recovered by amalgamation with mercury). The manganese-stained silver veins baffled them. Rich silver ore was recognized in one vein in 1865, but attempts to extract the silver failed. By 1876, however, metallurgical problems were solved. The peak of silver mining came at Butte in 1887, when five silver mills were operating.

The Anaconda in 1881 was a silver prospect. At a depth of 100 feet a narrow seam of copper sulfide was exposed, and on the 300 foot level a vein of ore containing abundant copper sulfides, five feet in width, was cut. The copper ore was originally shipped to Swansea, Wales, for smelting but soon local smelters obviated the need for further shipments overseas. Between 1884 and 1897, Anaconda ore averaged about five percent copper and four ounces of silver per ton.[87] This metal content was typical of the high-grade copper veins.

The Old Dominion mine at Globe, Arizona, 60 miles east of Phoenix, was brought into production in 1881 as the first of the Arizona copper districts, although the claims were staked in 1875 in the hope that the deposit was one of silver. The copper mineral deposit was vein-like, lying along a fault, and most of the early ore mined (up to 1903) was copper oxide ranging in grade between six and 20 percent copper.[88] The Old Dominion closed for good during the Depression of the early 1930's, but the district remained an important source of copper because of other mines developed later at nearby Miami and Inspiration. At Bisbee, in Southern Arizona, high-grade oxidized copper deposits in limestone became an important source of copper beginning in 1885.[89]

The Jerome district, 100 miles north of Phoenix, Arizona, belongs with the high-grade copper deposits of the late 1800's, although mining there persisted well into the middle of the 20th Century. The first claims on the Jerome copper deposit were staked in 1876. Dr. James Douglas, the founder of Bisbee, examined the Jerome prospect in 1880. He recommended its development but warned that no profit could be expected until the Santa Fe Railroad, which was building west from Albuquerque, reached Ash Fork, 40 miles north of Jerome. The United Verde Company was incorporated in 1882, and the Santa Fe reached Ash Fork in 1883.

A copper smelter was constructed near Jerome, the parts for it being hauled by wagon over the mountains from Ash Fork. Coke for the smelter came from Wales, around the Horn by ship to San Francisco, thence by rail to Ash Fork, and last by wagon to Jerome. The resultant high costs together with poor management caused the United Verde to fail in 1887, but the deposit was purchased in 1888 by W. A. Clark of Butte fame. A narrow-gauge railroad was built connecting Ash Fork with Jerome, a new smelter was installed, and the era of fabulous production and profits from the United Verde began.[90]

Geologically, the United Verde deposit was a volcanic pipe 800 x 700 feet across and over 3,000 feet deep, intruded in ancient schists. It consisted of massive sulfides of copper and iron with quartz. In the closing years of mining, the average grade was five to six percent copper, with considerable silver. Earlier ore mined ran much higher.[91] The United Verde Extension ore body, discovered in 1914, lay on the opposite side of a fault from the original United Verde ore body. It actually was the former top portion of that pipe, sliced off and moved downward by the faulting. In 1916 the grade of ore produced from the Extension was nearly 24 percent copper.[92]

The Magma copper mine at Superior, 60 miles east of Phoenix, Arizona, is a major example of the high-grade copper vein type of deposit. The outcrop of the fault along which the magma copper ore bodies lie was discovered in 1875 during a search for a silver deposit comparable to that of the Silver King, a highly successful silver mine not far away. Being a copper deposit, the Magma ore deposit disappointed the old-timers who found it, and there was little or no production until the mine was acquired by its present owners, the Magma Copper Company, in 1910. At that time the property was 30 miles from a railroad and during the early life of the mine all supplies had to be hauled in by wagon at a cost of $10 per ton. A narrow-gauge railroad was constructed in 1914, followed later by a standard gauge line. A small concentrator was built in 1913 and was later greatly enlarged. A smelter was put in operation in 1924.[93]

The oxidized ore near the surface at Magma was very rich. Shipments in 1912 averaged 48 percent copper and 68 ounces of silver per ton. Second-class ore averaged 16 percent copper and 18 ounces of silver per ton.[94] The sulfide ore was, of course, much lower in copper content, but was still relatively high-grade. In 1925 sulfide ore on the 2,000 foot level averaged better than six percent copper.[95] The ore today averages about five percent copper.

Early mining at Silver Bell, 35 miles northwest of Tucson, Arizona, deserves mention with the high-grade deposits of the late 1800's, although Silver Bell later became a "porphyry" copper. The mining of oxidized copper ores from replacement deposits in limestone started in 1865 at Silver Bell. The copper was smelted locally. By 1909, 45 million pounds of copper had been produced from the district.

The high-grade copper deposits that have been mentioned were all discovered in 1877 or earlier, most of them as a result of the search for precious metals, particularly silver. Unlike the gold, silver, and lead-silver deposits, however, where mining usually began shortly after discovery, with copper there was commonly considerable lag between discovery and production. The lag was not universal, of course. At Silver Bell, production of oxidized copper ore, starting in 1865, probably came not long after discovery. At Morenci, where oxidized copper ores were found in 1872, the lag was only three years. The Old Dominion ore body at Globe was found in 1875, but to bring it to production took six years. The high-grade oxidized copper ores in the limestone at Bisbee were first recognized in 1877, but it took eight years to bring these to production. At Butte, where attention was first paid to the copper veins in 1872, the lag was 12 years, and although the Jerome copper deposits were discovered in 1876, it was 18 years before substantial production began. Finally, the Magma deposit was found in 1875, but 35 years elapsed before substantial production started.

Neither large scale underground mining by block-caving nor open pit mining were familiar to western miners before the Bingham open pit was successfully put into production in 1907. Both methods were imported from the Lake Superior iron country of Michigan and Minnesota. The consideration of large, low-grade copper deposits as economic resources had to await the arrival of these cheap mining methods, together with the perfection of methods for concentrating low-grade sulfide minerals.

The pioneer and prototype of the large scale "porphyry" coppers was the disseminated copper mineralization found in the large intrusive mass of granite-type rock at Bingham, 20

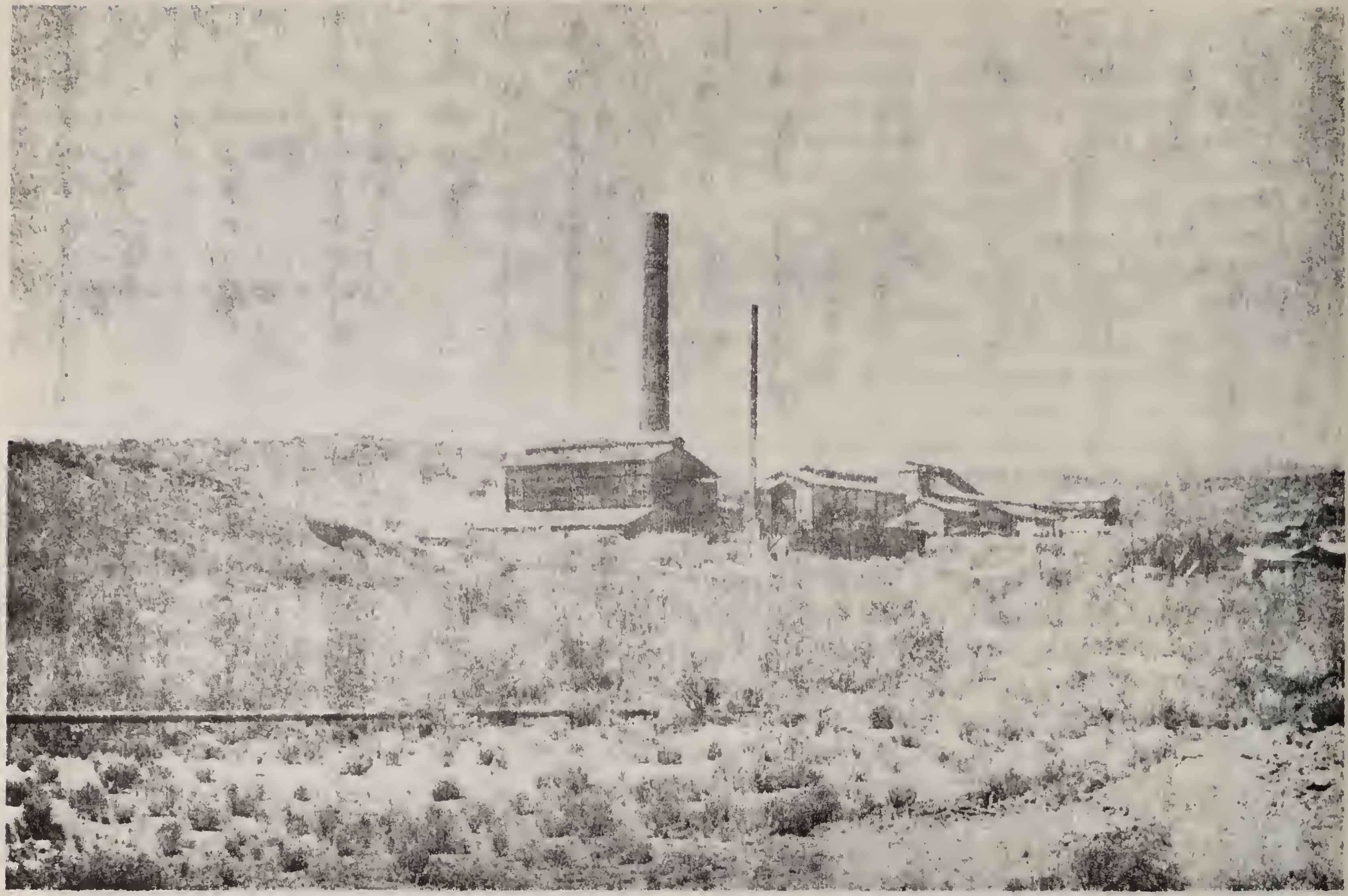


Fig. 30 – The copper smelter at Superior, Arizona. Built in 1924, the smelter was designed to produce copper metal from the rich (five to six percent copper) ores produced by the Magma Mine from vein and massive sulfide replacement deopsits in limestone. Discovered by men looking for silver, the first significant production from the Magma deposit started about 1910. Earliest ores contained almost 50 percent copper and nearly 70 ounces of silver per ton.

miles southwest of Salt Lake City, Utah. In 1887 one E. A. Wall sampled an outcrop and an old tunnel at Bingham. The tunnel, which exhibited copper sulfides, averaged 2.4 percent copper. The Highland Boy Mine, situated just west of the intrusive mass, made its first shipment of high-grade copper ore (which occurred in limestone) in 1896. By that time, Wall had control of 200 acres (10 lode claims) of ground within the intrusive mass and had driven more than 3,000 feet of mine workings.

The property was sampled by D. C. Jackling in 1898, and he estimated "proven" ore at 12,385,000 tons averaging two percent copper, with 25,000,000 tons of "probable" ore. The sampling was checked by a pilot mill. Recovery was 72 percent and the grade was raised to 22 percent copper in concentrates. This was well above the usual grade of high-grade copper deposits developed in the late 1800's. Raising the grade of ore by beneficiation required an investment, however, in the form of an expensive mill. No profit could be made on low-grade copper ores without mass production to lower unit costs. Even six percent copper ore was not economically valuable at the small scale of production at the Old Dominion mine in 1903.

Utah Copper owes its being to the faith that Daniel Jackling had in it. After several deals fell through, Jackling at last secured an option from Wall and went for financial backing to the Penrose Brothers, then very active and successful in western mining. After more testing of the deposit, the Utah Copper Company was organized in 1903. Only $250,000 in cash was available at the start. Several million dollars still had to be found. The Guggenheim Exploration Company and Hayden, Stone and Company underwrote several bond and stock issues, mainly to build the Magma mill at Garfield, Utah. Capitalization was then $7.5

million. After a further increase in capitalization, production from the open pit started in 1907.[96] The success at Bingham set off a chain reaction and a decided geographic shift in the centers of copper supply, mainly to the Southwest, in Arizona and New Mexico.

The first successor to Utah Copper was at Ely, in Eastern Nevada. Jackling was involved there also, with the Nevada Consolidated Copper Company organized in 1904, controlled by the Utah Copper Company. First production from the porphyry copper deposit at Ruth, near Ely, was recorded in 1908.[97] In 1911 the underground block-caving of disseminated copper ore began at Ray, 70 miles southeast of Phoenix, Arizona. In the same year, underground mining by block-caving of the Miami Copper Company deposit began at Miami, Arizona, 16 miles northeast of Ray. Until the late 1920's, the grade of ore averaged about two percent copper, higher than most of the other porphyry copper ore deposits.[98] In 1911 production started also at Santa Rita in Southwestern New Mexico where the small-scale mining of oxidized copper ores and native copper had been going on sporadically for over 100 years.[99] The Inspiration Consolidated Copper Company was incorporated in the same year, after several sporadic and mostly unsuccessful attempts at mining the copper ore on the property it had inherited in the Globe-Miami district of Arizona.

The next porphyry copper deposit to come into production was the New Cornelia at Ajo, Arizona, 120 miles west of Tucson. There is evidence that the Ajo deposits were known and worked during the 16th Century and perhaps earlier by the indigenous inhabitants of the area. Spanish miners may have worked some of the high-grade copper veins as early as 1750. From 1854 to 1859, Americans mined high-grade copper ore at Ajo and hauled it by wagon to Yuma from which point it was taken for smelting to Swansea, Wales, in sailing ships. From 1860 to 1911, similar high-grade mining attempts failed for a variety of reasons, including the transportation problem and an apparent excess of less than honest stock promotes. In 1911 the property was acquired by the Calumet and Arizona Company of Bisbee, and drilling in the next two years delimited what was then considered to be the ore body. Oxidized copper minerals overlay the sulfides, and it took three more years to develop a method of successfully extracting copper from the oxides. Mining of the oxide minerals by open pit began in 1917. By 1930 the oxide ore was mined out, but a concentrator for treating sulfides had been built in 1924. After 1930, sulfide ore only was produced.[100]

At Morenci, Arizona, there was mining and concentrating of ore containing from three to four percent copper from 1904 to 1932. Although its existence in the Morenci district was known, the coming into production of the great Clay ore body, containing nearly half a billion tons of ore averaging 0.8 percent copper, was delayed by the Great Depression. World War II changed conditions, however, and it did come into production in 1942 at a cost in capital investment of $76 million.[101]

Although the San Manuel porphyry copper deposit, 45 miles northeast of Tucson, Arizona, did not come into production until 1956, an initial ore body had been largely delimited by 1947. The copper-bearing porphyry cropped out only in a very small area, the rest of the upper surface of the deposit being covered by rocks later than the mineralization. The Magma Copper Company, in fact, turned down a chance to acquire the property in 1941. During World War II, however, the U.S. Geological Survey and U.S. Bureau of Mines were directed to add copper to the list of strategic minerals urgently needed for the war. By 1945 drilling by the Bureau of Mines had delimited a deposit of 30 million tons averaging 0.8 percent copper. Half of this tonnage was oxidized, mainly in the form of copper silicates. Magma came back into the picture and started drilling on their own in 1944. Results caused them to exercise a previously acquired option in 1945. The initial drilling was completed in 1948 after having cost $2.5 million.[102]

While the development of copper resources in the West lagged behind that of the precious metals, that of zinc lagged decidely behind that of copper. This was for several reasons, both economic and physical. In the first place, uses for zinc were limited in the early days, with galvanized iron, one of the major uses of zinc, only gradually coming into acceptance. Another reason was metallurgical. Zinc is a pesky metal when associated in a mineral deposit with other metals such as lead, and it offers so much trouble in smelting that lead ores or concentrates are penalized if they contain more than a small amount of zinc. Nearly all of the western lead-silver deposits known in the 1800's contained zinc as an impurity. Even today, there are few deposits in the West valuable for zinc alone. One of these, however, is the deposit at Hanover, in Southwestern New Mexico, where zinc ores occur in limestone adjacent to a granitic intrusive. The New Jersey Zinc Company started mining this deposit in 1902. The ore averaged 13 percent zinc and was particularly valuable because it contained practically no lead. The zinc occurred with magnetite, which was separated initially by a magnetic concentrator although froth flotation was later used.[103]

Magdalena, 100 miles north of Hanover, was another early camp supplying mainly zinc, although lead and precious metals occurred there as well. The Magdalena ore bodies, like those of Hanover, were found in limestone. Production of zinc at Magdalena began in 1903.[104]

In Utah, zinc deposits were developed first in 1904, in the San Francisco and other districts of Beaver County, in the southwestern part of the state.[105] In the following year, deposits at Park City, Utah, began to yield zinc, and these were followed by Goodsprings, Nevada, in 1906.[106] Production of zinc at Bingham began in 1909[107] and at Tintic in 1912.[108]

Prior to World War I, there was little demand for molybdenum and domestic resources consisted only of small, scattered deposits. The First World War stimulated demand for molybdenum, however, as an alloying agent to make harder, stronger steel. By 1915, production had expanded to the largest amount by then recorded – 3,498 tons of ore containing 181,769 pounds of molybdenum. Arizona furnished most of this from wulfenite ore at the Duquesne mine near Patagonia in the southern part of the state and the Leviathan mine near Wikieup in the north. A considerable quantity of ore was also obtained from the Climax molybdenum deposit in Colorado and some additional production came from mines in Nevada and Montana.[109] By 1918 domestic molybdenum production reached a new high of nearly 900,000 pounds. Deposits at Climax, Colorado, and Questa, New Mexico, accounted for a large portion of this production.

Following World War I, demand for molybdenum fell rapidly, and in 1920 the only recorded production was less than 2,000 tons of ore. In 1923 demand for molybdenum started up again, however, and the new production came largely from ores at Questa. In 1924 Climax resumed production and, with Questa, produced nearly 300,000 pounds of molybdenum. From 1924 on, the Climax deposit has maintained Colorado's position as the nation's leading source of molybdenum except for brief periods in the late 1940's and early 1950's when by-product production of molybdenum from the Bingham Canyon, Utah, copper mine exceeded Climax's production. By-product molybdenum found in disseminated copper deposits in the Western United States accounted for most of the remaining domestic molybdenum supply prior to 1947.

Since the middle of the last century, California has been the main source of mercury in the United States. The New Almaden mine south of San Francisco started production in 1850. The new Idria mine, in the same general area, started in 1858. Most past and present producing deposits had been found by 1875. Prior to 1898, California provided all of the nation's domestic mercury supply. After that time commercial deposits were discovered in other western states, mainly Nevada, Oregon, and later, Idaho.

The development of the iron resources of the West had to wait for the growth of regional markets and adequate transportation. In 1893 a trial shipment of iron ore from the Buena Vista Hills district southeast of Lovelock, Nevada, was made to the Union Iron Works at San Francisco, but no continuous commercial production resulted at that time. In 1903 the Barth iron ore deposit, 30 miles wouthwest of Elko, Nevada, was leased to the American Smelting and Refining Company to provide flux for their Murray, Utah, lead smelter. This source of supply was used until 1918. In 1943, the Buena Vista Hills district again became a source of iron ore. Production continued during World War II, but most of the ore was used in heavy concrete aggregate for ship ballast and not as a source of metallic iron.[110] Production slumped sharply after the War, but resumed in 1951.

Iron ore production started in the Hartville district of Wyoming in 1902. There, 80 miles north of Cheyenne, the deposits resemble the Lake Superior iron ore deposits. The area seems to have been a fairly continuous source of supply ever since the early 1900's. By 1960, the deposits had yielded 30 million tons of ore.[111] In California, no iron ore was produced to speak of until 1942, when the Kaiser Steel Company opened the Vulcan iron mine in San Bernardino County to supply their steel plant at Fontana.

In Utah, the mining of iron ore deposits commenced in 1852 but remained sporadic until the early 1920's, when the availability of local coking coal and the promise of western markets brought about the establishment of a steel works by the Columbia-Geneva Division of the United States Steel Corporation, at Provo, 30 miles south of Salt Lake City. Practically all of the iron ore for the Provo mill came from Iron Springs district in far Southwestern Utah. Utah has continued to be a major source of iron ore production in the West, and the Iron Springs district is still virtually the sole source of ore in that state.[112]

The development of industrial minerals resources in the West closely paralleled, in most cases, the development of copper and iron resources. The major exception was limestone, deposits of which had been worked even before 1872.

The western phosphate field, where phosphates occur in Paleozoic sediments, extends from the latitude of Salt Lake City northward 350 miles to Helena, Montana. The width of the field is about 100 miles (see Figure 22).[113] It includes parts of Utah, Wyoming, Idaho, and Montana. Production of phosphates in the West began in 1906 in Southeastern Idaho. In 1907 limited production started in Utah and Wyoming. Production did not start in Western Montana until 1923. In the East, however, the utilization of the so-called land-pebble deposits had begun in Florida in 1888, and production from deposits in Tennessee began in 1894.[114] Domestic phosphate production in 1946 included five million tons from Florida, 1.4 million tons from Tennessee, 1.2 million tons from Montana, and about 300 thousand tons from Idaho.[115]

Minor amounts of asbestos were produced in Vermont and California for many years prior to 1947. Arizona appears to have been the first western state to provide asbestos on a commercial scale. Between 1914 and 1946, 21,000 tons were produced from the Chrysotile district, in the Salt River Canyon 35 miles northeast of Globe, Arizona.

The development of potash resources in the United States did not come until after World War I during which normal supplies from European sources were curtailed. In 1925, drillers looking for oil in the Permian Basin area east of Carlsbad, New Mexico, cut through saline deposits containing potassium salts at a depth of approximately 1,000 feet. Late in the 1920's and in the early 1930's several firms began development of the deposits in the Carlsbad area. By 1947 three firms were operating in the district. Previous to the development of the Carlsbad deposits, the nation's only mineral potash came from brine deposits at Searles Lake in California. Potassium salts had been produced there as early as 1916.

Fig. 31 - Underground mining of asbestos in the Chrysotile district of Central Arizona. Utilization of these industrial minerals deposits, like many others in the West, did not come until the development of western industry in the early 1900's. Even in recent years, however, these resources serve only as sporadic supplies of industrial minerals, and their value and use are heavily dependent upon regional and local economic conditions. (Photo courtesy U.S. Bureau of Mines)

C. CHANGES IN MINERAL RESOURCES SINCE 1947

1. Changes in Metallic Mineral Deposits

Exploration efforts since 1947 by the mining industry have resulted in the discovery of many new mineral deposits, increasing the nation's reserves of most of the major mineral commodities. Geologic studies and concepts, and geophysical tools, have been utilized more than ever before to make these discoveries. Advances in mining, extraction, and refining techniques as well as increasing levels of labor productivity have enabled existing mines to expand production and new mines to come into production from lower-grade mineral deposits.

The United States gold mining industry as a whole never recovered from Limitation Order L-208, issued early in World War II, which forbade the mining of gold except as a by-product of base metal mining critical to the war effort. In 1945, when the order was lifted, few gold mines except the Homestake mine in South Dakota reopened. In 1962, however, the Carlin gold deposit, about 20 miles west of Elko, Nevada, was discovered. The gold there occurs in extremely small particles, invisible to the naked eye, in ordinary-looking sedimentary rocks. The deposit in no way resembles other gold deposits previously known to prospectors or geologists. By 1965, 11 million tons of gold-bearing rock, with a gross metal content averaging $11.00 per ton, had been blocked out at Carlin by drilling and trenching.[116] The deposit is being mined by relatively cheap open pit methods, and today is the second largest producer of gold in the United States, after Homestake, the nation's traditional gold producer.

The Carlin discovery in the early 1960's prompted a search for similar deposits. The Cortez Joint Venture, composed of several United States and Canadian mining companies, subsequently found a similar deposit near the old silver camp of Cortez, 60 miles southwest of the Carlin mine. By 1967 they had delimited about three million tons of ore at Cortez, also with a gross value of $11.00 per ton and also amenable to open pit mining.[117]

With the practical exhaustion in the early 1940's of the Tonopah, Nevada, deposits, the last of the major "straight" silver mining districts in the United States ceased production. Since then, silver has been produced increasingly as a by-product of base metal mining. While the porphyry coppers carry a very low amount of silver per ton of copper ore, the production of ore is on such an immense scale (some mines yield as much as 20 million tons of ore a year and one yields 35 million) that their contribution to silver production has become quite significant. Nevertheless, the "Silver Belt" in the Coeur d'Alene district in Northern Idaho is today the greatest source of silver in the United States.

Unlike the mineral deposits of the United States east of the Rockies, zinc minerals usually occur with lead minerals in the West. Although a number of important silver-lead-zinc deposits have been discovered in Canada in recent years, no really new deposits have been found in the Western United States since long before 1947. The Coeur d'Alene district in Northern Idaho, which is essentially a lead-zinc-silver district, is still the major source of lead and zinc reserves in the West and will probably be still producing in 1985, because the major companies operating there have embarked on a venturesome, imaginative exploration program, and the veins apparently carry ore to great depths. At Tintic, Utah, silver-lead-zinc mineral deposits developed since 1947 also give hope of similar future discoveries in that district.[118]

The outstanding development in western iron mining since 1947 has been the bringing into production of low-grade taconite ore near Atlantic City, 10 miles south of Lander, Wyoming, by the Columbia-Geneva Division of United States Steel. By 1961, 300 million tons of ore averaging from 22 to 35 percent iron had been blocked out. The ore must be concentrated and the concentrates are pelletized for blast furnace use.

The first major copper deposit to come into consideration after 1947 was the Yerington porphyry copper, 50 miles southeast of Reno, Nevada. The deposit lies east of the Old Yerington district, where copper minerals occurred in limestone adjacent to an intrusive

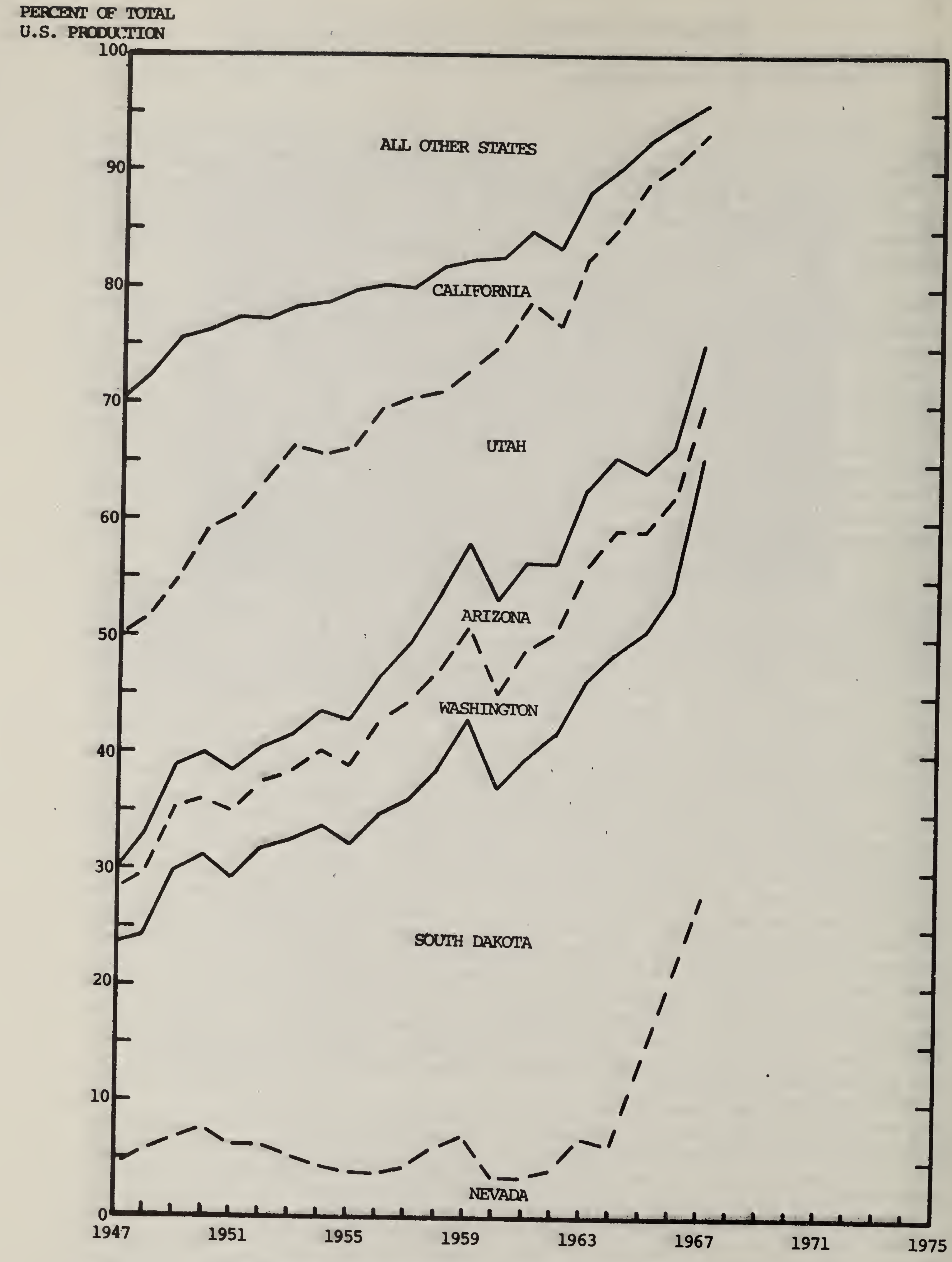


Fig. 32 - Geographic Distribution of Gold Production in the United States

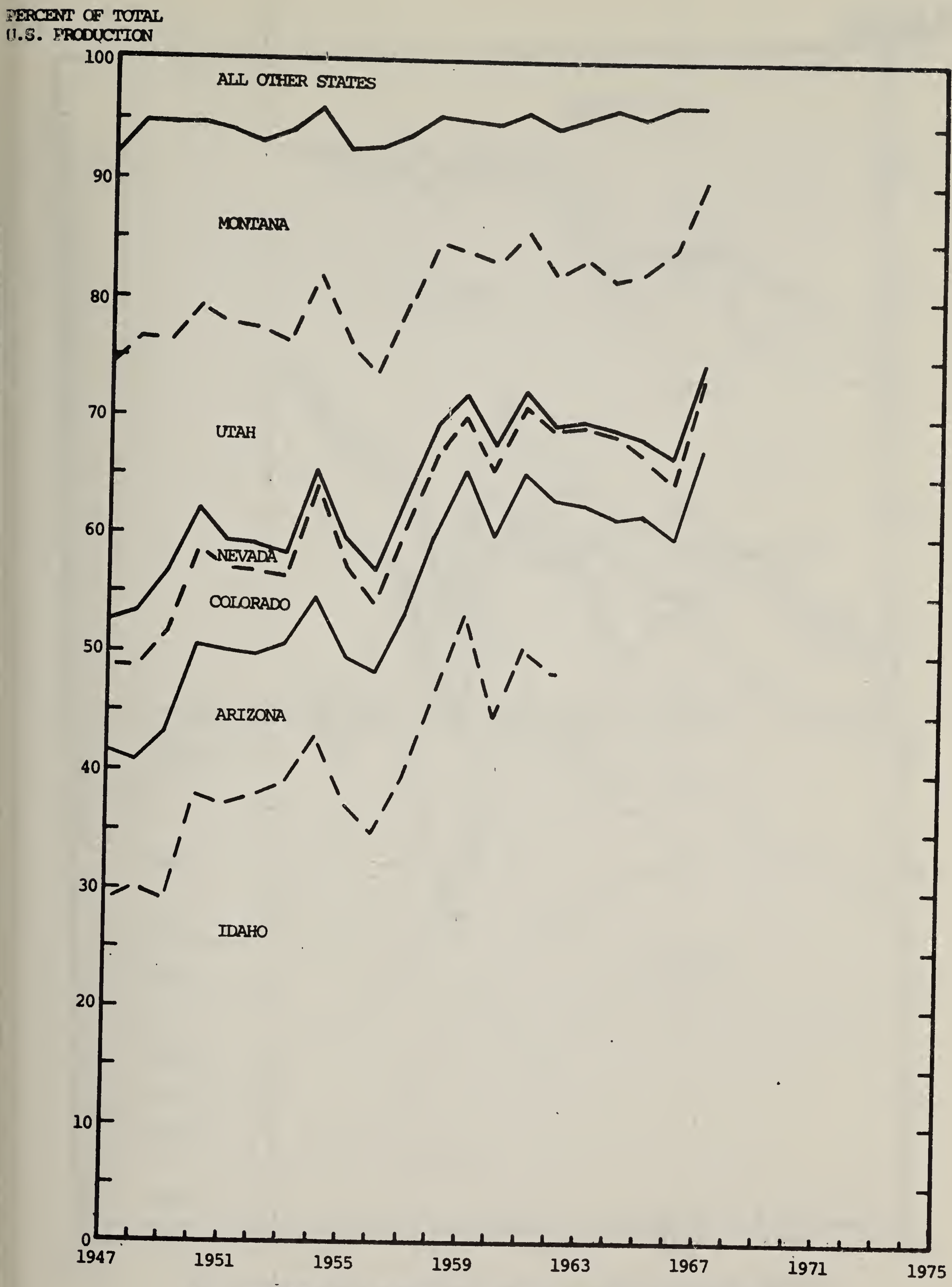


Fig. 33 - Geographic Distribution of Silver Production in the United States.

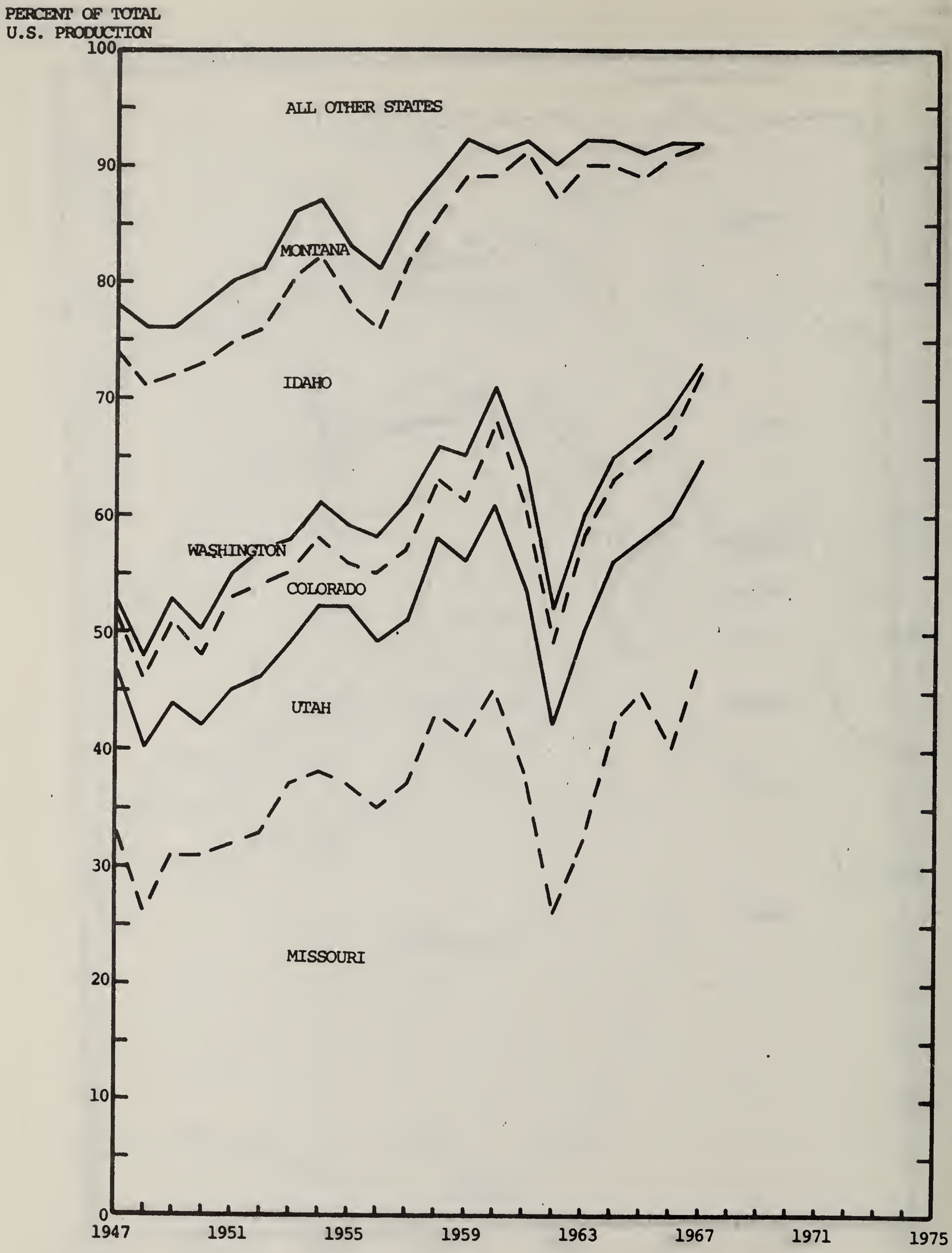


Fig. 34 - Geographic Distribution of Lead Production in the United States.

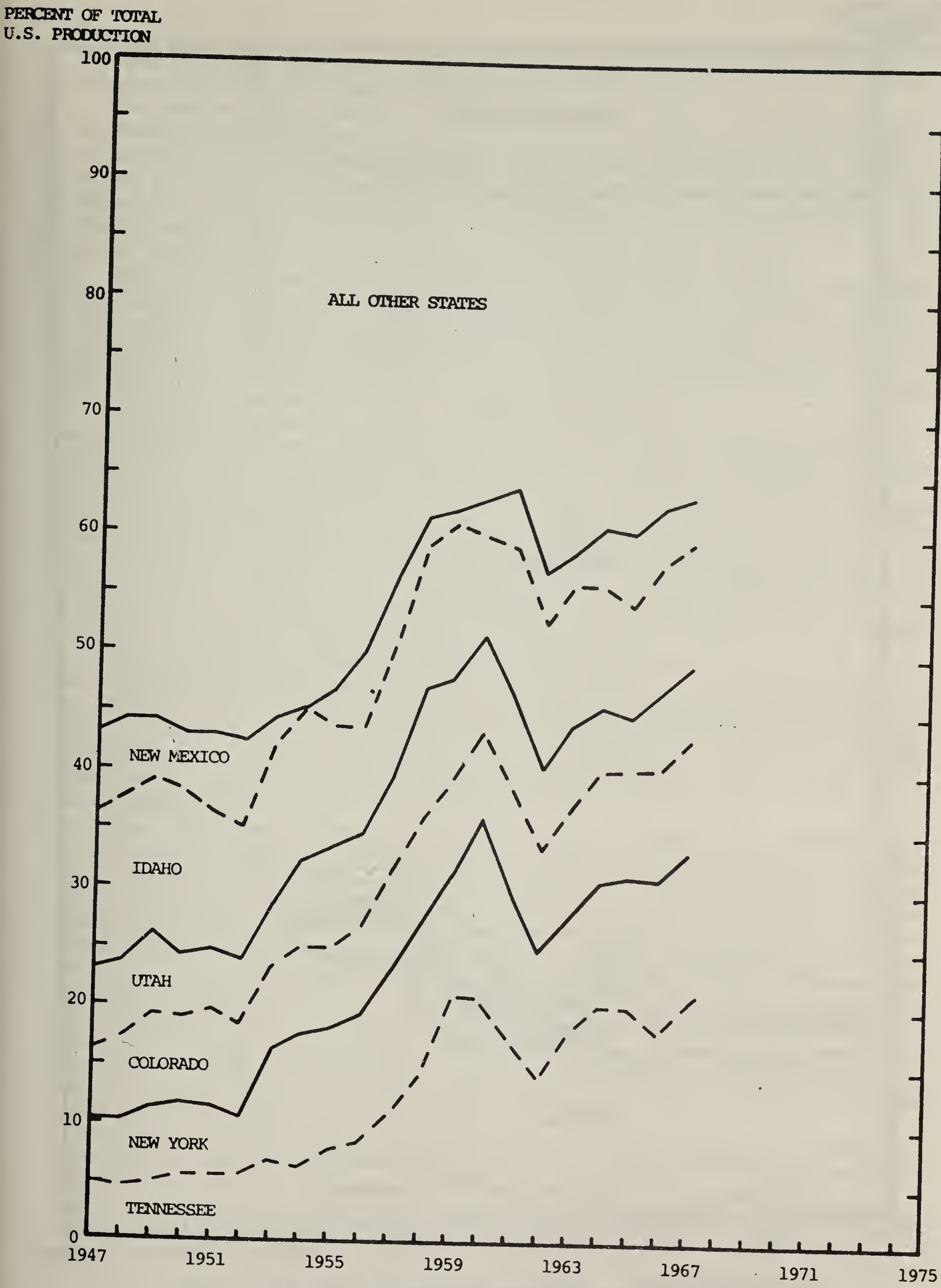


Fig. 35 - Geographic Distribution of Zinc Production in the United States.

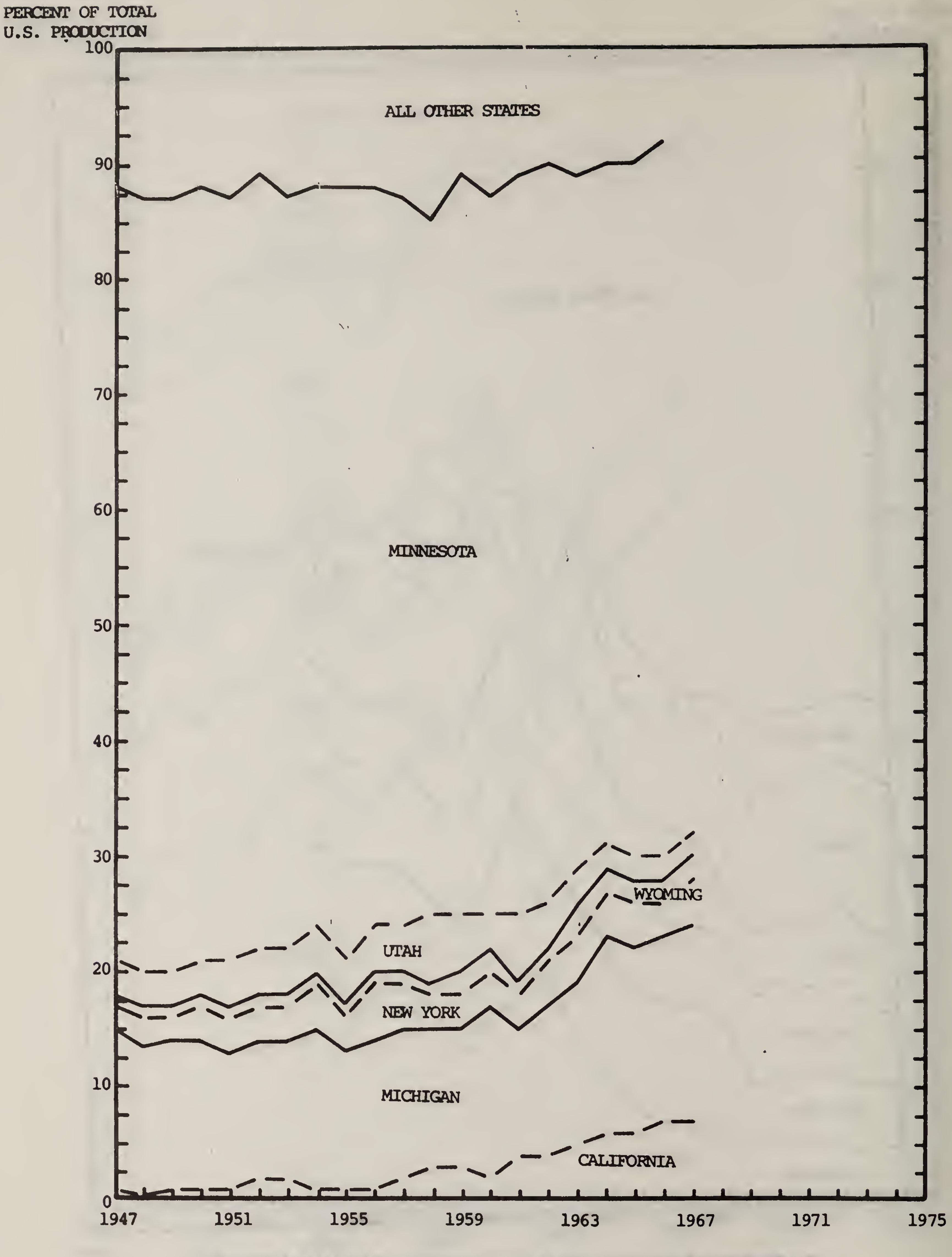


Fig. 36 - Geographic Distribution of Iron Ore Production in the United States.

body of granitic rock. Production of copper took place here between 1912 and 1930. The Anaconda Company drilled the Yerington porphyry deposit between 1941 and 1945, and commenced open pit operations in 1953.[119]

The early deposits of oxidized copper ore in limestone at Silver Bell, 35 miles northwest of Tucson, Arizona, have been mentioned. The American Smelting and Refining Company started exploratory drilling of the porphyry masses there in 1948 and commenced open pit mining in 1954.[120] In the same year, open pit mining of porphyry copper was resumed at Bisbee. The earlier open pit mining of the Sacramento Hill Pit extended from 1923 to 1929. Drilling, beginning in 1950, indicated an extension to the east of the ore body formerly mined. The Lavender Pit started production from this extension in 1954.[121]

The San Manuel porphyry copper deposit had been delimited by drilling before 1947. Since (because of depth to ore) mining had to be underground, expensive preparations had to be made – including shaft sinking (five different shafts), the driving of production and haulage levels, and stope preparation. For this reason, although development of the mine started in 1948, actual production did not start until 1956, and full production at the rate of 30,000 tons of ore per day was not reached until mid-1957.[122]

In 1950 geophysical exploration by the United Geophysical Company discovered the Pima copper deposit (about 25 miles south of Tucson, Arizona) *without any visible surface evidence of copper minerals in place*, although the geophysical indications were later checked by drilling. The surface over the Pima deposit was entirely covered by alluvium. Pima thus became the first major non-ferrous metallic mineral deposit in the United States to be discovered by purely geophysical methods. Mining at Pima began underground, and in 1952 and 1953, 67,000 tons of six percent copper ore were shipped from the property. The Pima ore body originally found was a high-grade nucleus, surrounded by low-grade mineralized area only minable by open pit. Further exploratory drilling delimited this ore and open pit production started at the beginning of 1957.[123]

The Pima discovery stimulated exploration in the same area and resulted in the finding of deposits containing hundreds of millions of tons of porphyry copper ore, all discovered by drilling beneath the valley alluvium. In 1959 the Esperanza deposit, in the southern part of the district, was brought into production. The Mission deposit, north of the Pima deposit, was placed in production by American Smelting and Refining Company in 1961.[124] The Twin Buttes deposit of Banner and Anaconda, in the southern part of the district, is scheduled for production by late 1969.[125]

Other copper ore deposits at scattered locations throughout the Southwest were developed both before and during the activity in the Pima-Twin Buttes district. In 1954, the Miami Copper Company began production from its Copper Cities deposit east of Miami, Arizona. The Copper Cities property was developed specifically to replace the exhausted Castle Dome deposit several miles to the west. Although both the Castle Dome and Miami copper deposits are no longer considered minable ore deposits in the traditional sense, they continue to provide copper for leaching operations. At Castle Dome, rock that was previously removed as waste presently serves as a source of copper while at Miami itself, rock considered too low in copper content to be minable by the underground methods used there prior to 1959 is still providing copper for leaching operations and in effect still represents a valuable mineral deposit. In 1963, the Miami deposit was the 24th largest source of mined copper in the United States despite the fact that at the time it had been closed down as a traditional mining operation for four years.

Not too far from the Globe-Miami district, the Christmas deposit of the Inspiration Consolidated Copper Company was developed in the mid-1960's. At first the relatively high-grade vein and replacement deposits were considered to be the important source of ore at Christmas. Subsequent difficulties in underground operations and resulting high costs, however, caused the producer to turn to a relatively low-grade area of copper mineralization adjacent to the higher-grade deposit. Subsequent production has been from the low-grade area and not from the high-grade portion of the deposit.

Also in the mid-1960's, a major porphyry copper deposit was developed at Mineral Park

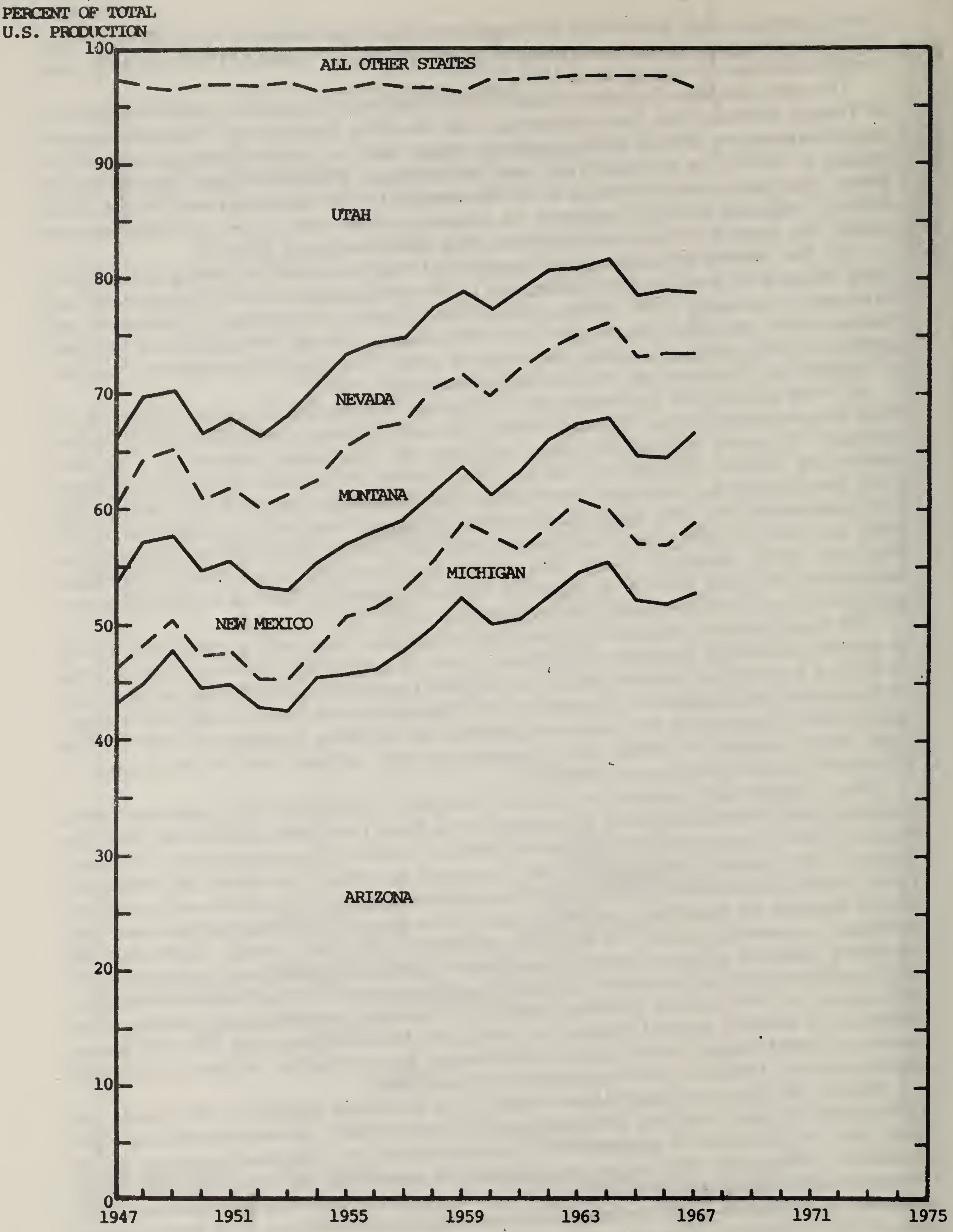


Fig. 37 - Geographic Distribution of Copper Production in the United States.

near Kingman in Northern Arizona, in an area more noted for gold than copper. The Ithaca Peak deposit developed there by the Duval Corporation also contained significant amounts of molybdenum sulfide.[126] In the late 1960's, the same company developed another major copper deposit near Battle Mountain, Nevada, in an area long known to be the site of small, high-grade copper deposits.

Not all of the significant copper deposits opened in the period since 1947 were in the West. Indeed one of the more important new properties is located in Upper Michigan, in the very area that saw the beginning of significant copper mining in the United States. In mid-1954 the White Pine property of the Copper Range Company was brought into production in the native copper district of Northern Michigan.

Another new copper deposit that was brought into utilization east of the Mississippi after the close of World War II was the Ore Knob deposit owned by Appalachian Sulfides, Inc., in North Carolina on the Eastern edge of the Appalachians. Appalachian Sulfides, which had been the Vermont Copper Company, Inc., prior to 1954, brought the Ore Knob deposit into production in early 1957. The following year the company ceased operations at its Elizabeth copper deposit in Vermont. Production from the Ore Knob deposit itself was halted in late 1962.

There was no notable production of nickel in the United States before the Hanna Nickel Smelting Company, a subsidiary of the Hanna Mining Company, started production of its plant at Riddle, Oregon, in 1954. Since that time, production of ferro-nickel from this laterite deposit has increased substantially.

Total domestic production of beryllium was negligible until 1941, when the oncoming war stimulated demand through the discovery of war-time uses for beryllium metal. Sources of domestic beryl were pegmatite dikes in Maine, New Hampshire, Colorado, and South Dakota. Deposits were not discovered in New Mexico until 1944. Between 1941 and 1962, United States production of beryl (plus the output of a low-grade ore mined in Colorado containing beryllium silicate as well as beryl) never exceeded 13 percent of imports, and fell at one time as low as three percent.[127]

Prior to 1960, reserves of beryllium ore in the United States were almost negligible and confined to small pegmatite deposits containing the mineral beryl. In 1960 enormous deposits of beryllium ore averaging about 0.5 percent beryllium oxide (in contrast to the 11 percent found in beryl) were discovered in Western Utah.

One of these deposits is now in production.

In general, the old centers of mercury production, in California and Nevada, have remained dominant since 1946, although several entirely new deposits have been found, and new ore bodies discovered in established areas. Stimulated by the present high price of mercury, however, attention is turning to the possibility of mining large, low-grade deposits amenable to open pit mining. In 1966, 73 percent of the nation's mercury production came from California, 15 percent from Nevada, five percent from Idaho and the rest from other states including Alaska.

Uranium had little use other than as a source of radium for scientific and medical purposes, and as a pigment in glass and ceramics, prior to World War II. Foreign uranium deposits were richer and provided a cheaper source of radium. Domestic uranium ore production was small and sporadic. Nearly all of the nation's production came from the Uravan district and adjacent areas on the Colorado Plateau in Southeastern Utah and Southwestern Colorado. Development of the atomic bomb during World War II created the world's first real demand for large amounts of uranium. Early production was concentrated in the Uravan area. In the early 1950's new and larger deposits were discovered in Northwestern New Mexico, and the major portion of uranium production began to shift to the Ambrosia Lake area near Grants. Further exploration also resulted in the discovery of major deposits in Washington, Northeastern Arizona, and in Wyoming, but production from these states so far has been subordinate to that from New Mexico. In 1965 New Mexico

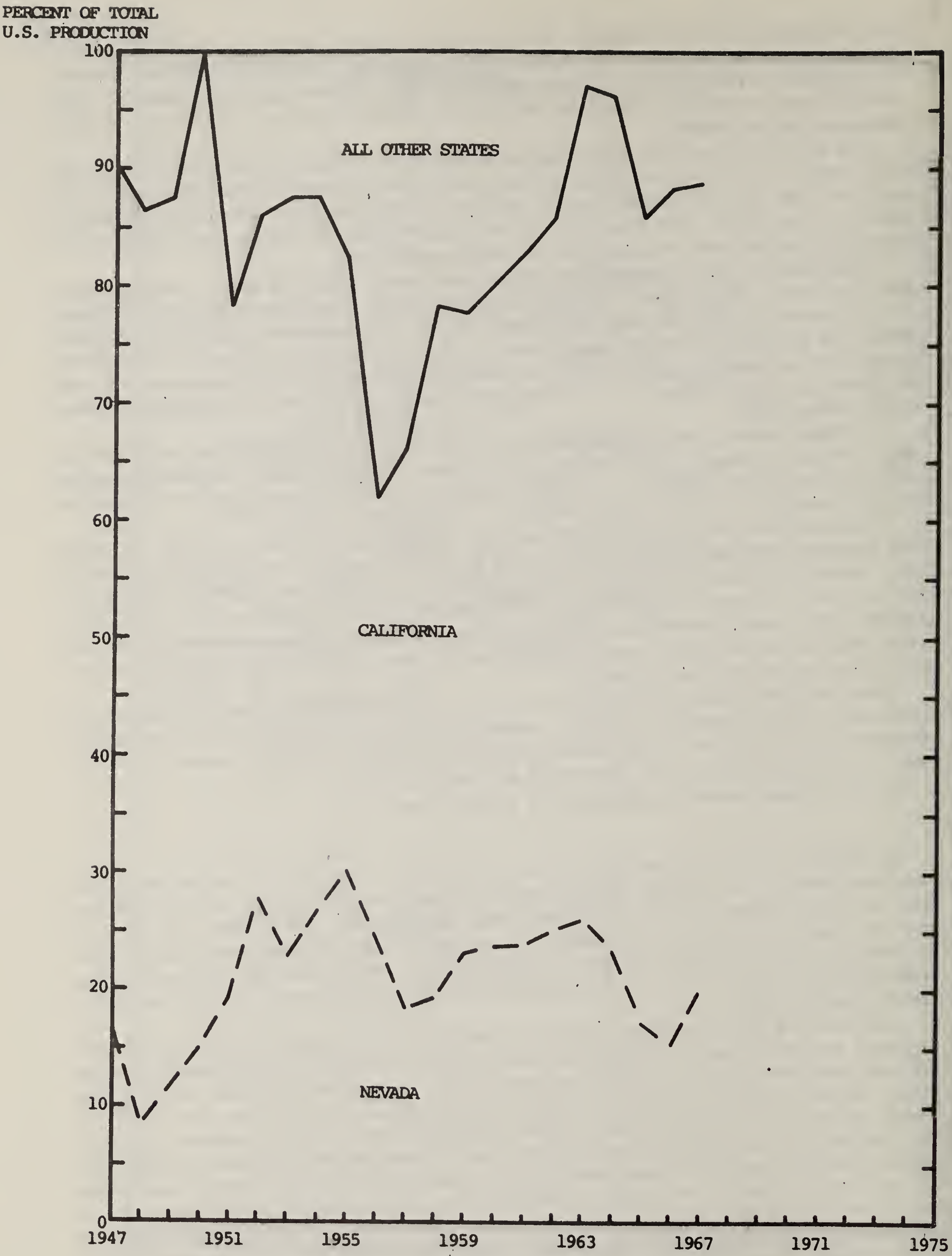


Fig. 38 - Geographic Distribution of Mercury Production in the United States.

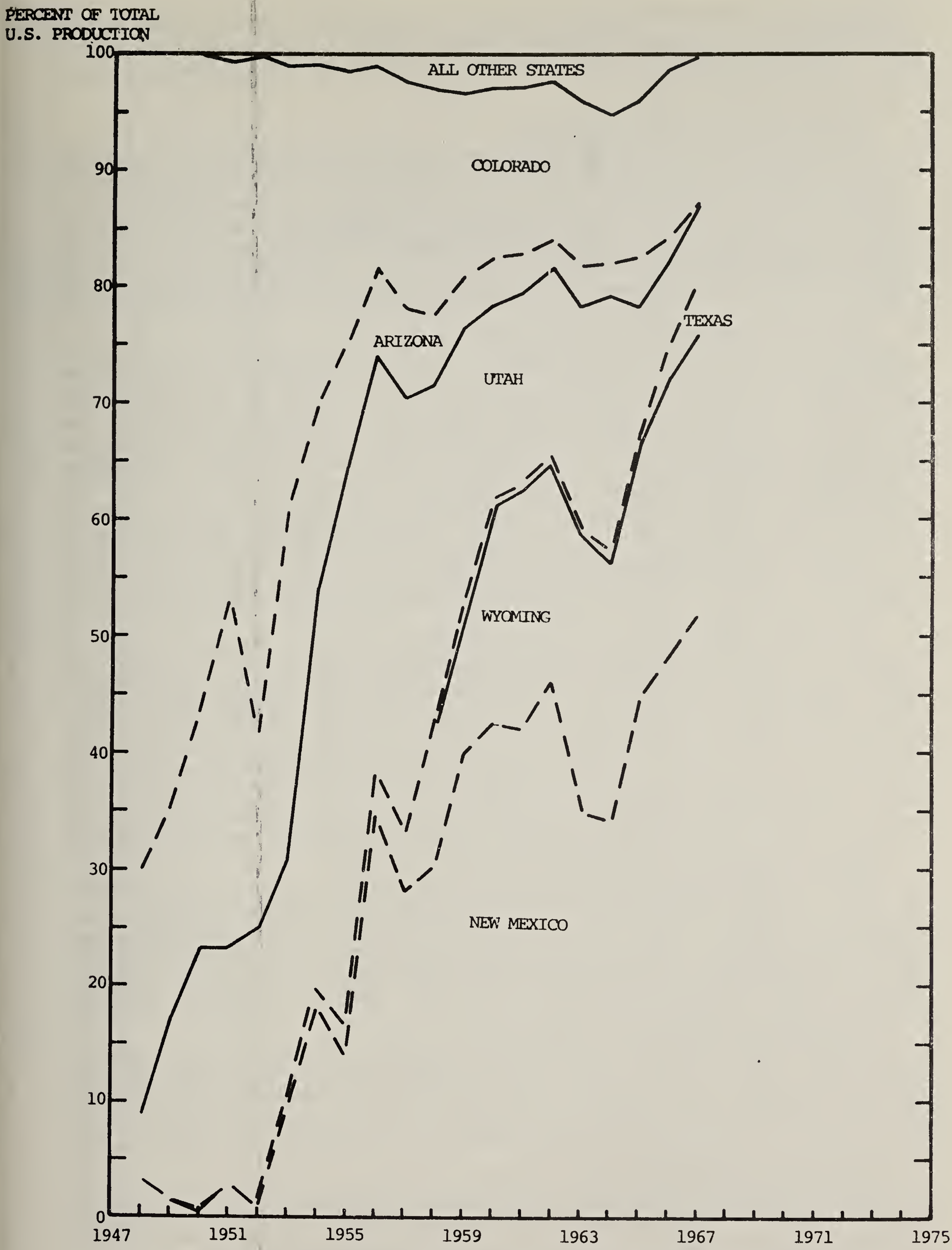


Fig. 39 - Geographic Distribution of Uranium Ore (U_3O_8) Production in the United States.

contributed 46 percent and Wyoming 24 percent of total domestic uranium production, and Colorado, Utah, Arizona, and Washington were the next largest producing states. In 1967, New Mexico contributed 54 percent, Wyoming 21 percent, Colorado 13 percent, and Utah six percent of total production.

2. Changes in Industrial Minerals Deposits

Known western deposits of industrial minerals have also increased since 1947, although many such resources still remain undiscovered or unevaluated. The nation's borate reserves remain at present incompletely determined and developed. Since 1947, operations have expanded and new mines have opened up (e.g., the Jenifer mine of Pacific Coast Borax Company, started in 1951) to satisfy rising demand.[128] New discoveries have increased *gypsum* reserves since 1947 in Arizona and other western states. These new deposits will increase in economic importance as urban growth continues to rise in the Western United States.

Limestone reserves have increased for the most part through expanded exploration, resulting in the discovery and development of many new deposits as well as additional evaluation of known deposits. Most of the larger limestone deposits developed in the West since 1947 have been used as a source of cement rock, but some have also been developed as sources of chemical and agricultural lime. Many small deposits of high purity and appropriate texture have also been utilized for roofing and other minor construction applications. Phosphate reserves in the West have increased since 1947 through the development of known deposits, new discoveries, and a lowering of the grade considered profitable for mining. In 1950 the *Paley Report* estimated the nation's minable reserves of about four billion long tons of which 1.5 billion were in the Western States and the balance in Tennessee and Florida. Potential reserves totaled at least eight billion tons, 6.5 billion tons of which were in the Western States. By 1967 marketable reserves[129] had increased to 14.5 billion long tons.

These reserve figures are based upon theoretical considerations of indicated grade and tonnage that might be mined, given the proper conditions. Useful reserves are much smaller than the above figures would indicate. Apart from the grade and tonnage in a given deposit, other (and equally critical or more so) factors are: waste to ore mining ratios, transportation (mine to plant and plant to consumer) costs, mining and processing costs (including the amount of cost required to remove impurities, which vary from deposit to deposit in amount and difficulty of extraction), royalty costs, and costs due to federal and state mining regulations and taxation policies. The grade and tonnage requisites for a valuable mineral deposit are widely divergent, therefore, for different localities, states, and for privately-owned as opposed to federally- or state-owned land.

Sodium mineral reserves have been increased since 1947 by continued development of the brine and *playa lake* deposits in California, as well as the discovery and development of the sodium carbonate deposits in the Green River formation of Wyoming, Colorado, and Utah. Known reserves of sodium carbonate and sodium sulfate are in excess of 354 and 261 million tons, respectively. Deposits of other sodium minerals associated with the oil shales in the Green River formation represent additional possible reserves, the quantity and quality of which are as yet completely unknown.

Largely through the discovery of the California deposits, domestic reserves of asbestos have increased from 1.55 million tons in 1952 to 5 million tons or more in 1967. In 1947 most known domestic asbestos deposits were in Vermont and Arizona. Sporadic production from those districts has continued, but the great shift in production centers was to California in 1962. In 1965 California produced nearly 75,000 tons of asbestos while Arizona produced less than 4,000 tons.[130]

Since the end of World War II, the number of potash deposits developed has increased. Starting in 1951 and extending through 1964, four more producers began to utilize the irregular deposits of potassium salts in the Carlsbad district. Over the same period, production from the Searles Lake deposit was expanded and other concentrations at Wendover and Moab, Utah, were developed and brought into production.

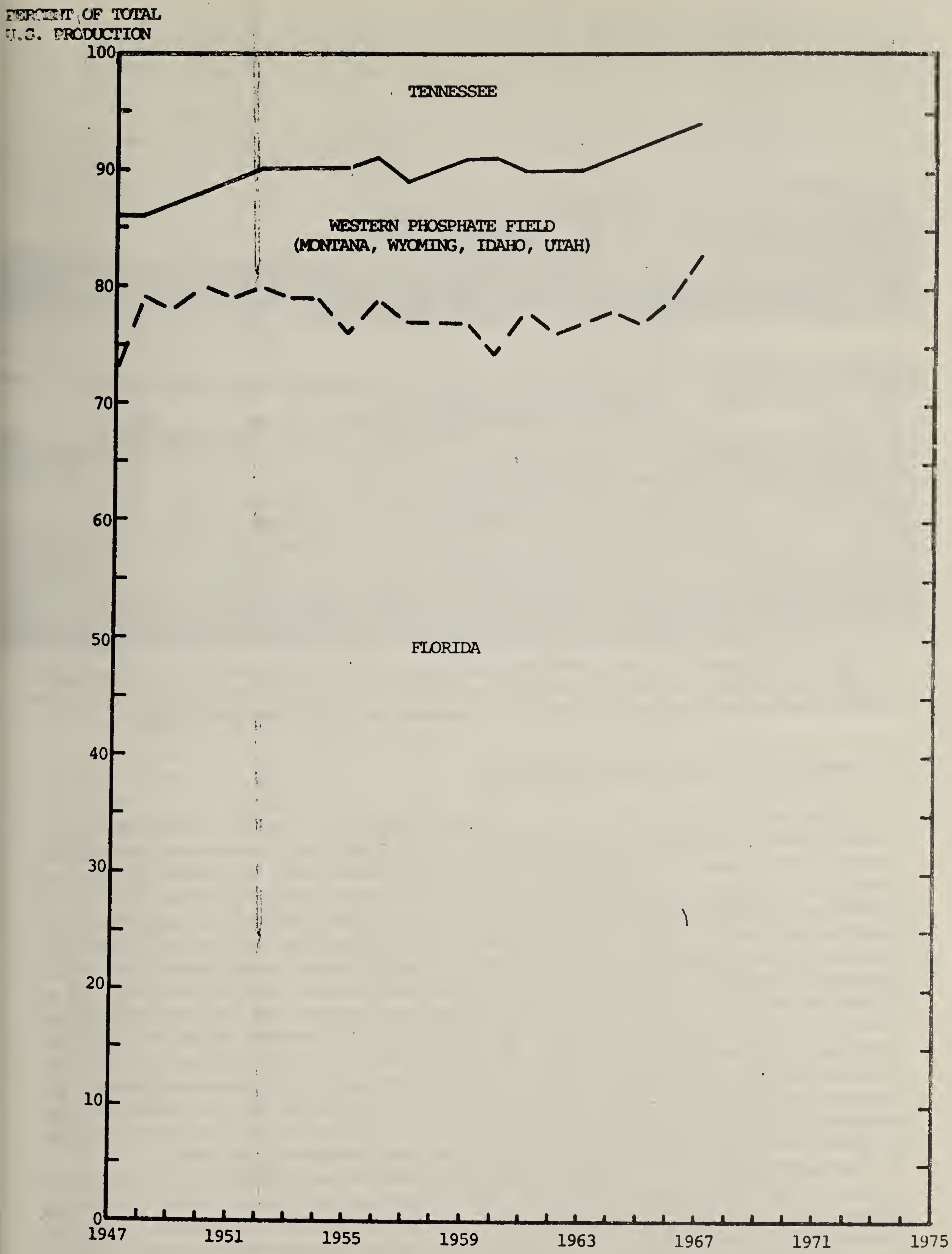


Fig. 40 - Geographic Distribution of Phosphate Rock Production in the United States.

Fig. 41 - Phosphate deposits in the Western Phosphate Field which covers parts of Utah, Idaho, Wyoming, and Montana. Although far less important to the nation as a whole than the Florida phosphate deposits, these western resources have maintained a consistent regional importance since 1947.

3. Changes in the Grade of Mineral Deposits

In the approximately two decades that have elapsed since the end of World War II, the average grades of mineral deposits mined in the United States have reflected changing technical and economic conditions. In some instances the grade of minable deposits has increased; in others it has declined. The average grade necessary for the commercial utilization of placer gold deposits has risen from five thousandths of an ounce per cubic yard in 1947 to more than eight thousandths of an ounce per cubic yard in 1967. The average economic grade of gold ore in place has also increased as the price of the yellow metal has remained constant in the face of rising mining costs. From 22 hundredths of an ounce per ton in 1947, the average grade of non-placer gold ore mined in the United States rose to 35 hundredths of an ounce in 1967. The average has remained relatively unchanged, with only slight variation since 1960, although it reached as high as 35 hundredths of an ounce as early as 1953. From 1953 to 1960 the average grade of gold ore mined in the country changed little. After 1961, there was a drop to about 33 hundredths and subsequently as low as 30 hundredths in the period 1963-1966. In 1967, however, there was a return to the 35 hundredths of an ounce per ton figure held during the 1950's.

The average grade of the nation's silver ore deposits has declined from the nearly 20 ounces per ton level existing in the late 1940's. Although there was an increase in average grade in the early 1950's to more than 22 ounces per ton and a return to this level again in the early 1960's, since 1961 the declining grade of silver ores has been relatively steady, to less than 14 ounces per ton in both 1966 and 1967. The variation in the average metal content of commercially minable silver deposits in the United States since 1947, however, has been highly erratic. Although at the present time average grade appears to be following a downward trend, it could again reverse itself, as it has done many times over the past 20 years.

The average quicksilver content of mercury ore mined in the United States has also followed an erratic pattern over the past two decades. From an average of more than 12 pounds per ton in 1947, the normal grade of mercury deposits declined to a low of about six pounds per ton in 1951 and 1955. After 1955 there was a rise to a high of more than 14 pounds per ton in 1962. Since 1962, however, there has been a sharp decrease in the average grade of mercury ores mined domestically, reaching a low of four pounds per ton in 1967.

Among the base metals, copper ore has persistently followed a steady downward trend in metallic content as larger and lower grade copper deposits have been brought into production. From a high of 0.9 percent copper in 1947, the average grade of copper mined in the United States has declined to a low of 0.6 percent in 1967.

The average grade of iron ore deposits mined in the United States has also followed a steady downward trend since the end of World War II. From an average of 41 percent iron in 1947, the grade of iron ore deposits mined in the country has declined rather steadily to less than 30 percent in the 1960's. By 1967, the average grade of iron ore deposits commercially useable in the United States had reached a low of 27 percent. The drop in grade after the mid-1950's was generally the result of the increased utilization of taconite deposits in Northern Minnesota.

Lead and zinc ores have followed opposite patterns in average grade since 1947. The average recoverable content of lead ores mined in the United States fell from a level of about 2.7 percent in 1947 to a low of 1.6 percent in 1957. From that time on, however, the average grade of lead deposits mined in the United States has increased rather substantially to a high of three percent in 1967. Undoubtedly part of the reason for this change has been the discovery of previously unknown higher-grade deposits in the new Viburnum district of Southern Missouri. Rising silver prices have also apparently increased the mining of lead-silver ores in some deposits in the West that were hard to mine but which contained greater amounts of lead than the more readily used straight lead ores.

The average grade of zinc ores mined in the United States increased and then dropped off between 1947 and 1967. From a level of about five percent zinc in 1947, the average grade of zinc ores mined in the nation climbed during the 1950's to a high of almost 14 percent in 1954. Subsequently, however, the average grade of zinc ores mined in the country dropped sharply to about five percent in 1956 and then declined rather steadily to less than four percent throughout most of the 1960's. In 1967, the average zinc ore mined in the United States contained 3.8 percent recoverable zinc.

Ores of two of the major steel alloying metals mined in the United States have declined in grade since 1947. Molybdenum has gone from a high of 0.32 percent in the early 1950's to about 0.20 percent in 1967. In the mid-1950's the decline was rather sharp, with the average grade of molybdenum deposits mined in the country reaching a low of 0.17 percent in 1964. The average grade of nickel ore mined in the United States has likewise declined, but only slightly. From the beginning of domestic operations in the mid-1950's, the average grade of ore mined has gone from 1.5 percent nickel down to 1.4 percent nickel in 1967.

The average grade of uranium ores mined in the United States has been rather erratic over the two decades since the end of World War II. From approximately 0.22 of a pound of U_3O_8 per ton in 1948, the average grade of deposits increased to a high of 0.33 per ton in 1952. Since the early 1950's, however, the average grade of uranium mined in the United States has declined rather steadily. By 1967, the average grade of uranium ore mined in the United States had again fallen to 0.20 of a pound of U_3O_8 per ton of ore mined.

Other metals, particularly those used in modern alloys, are mined from ores containing similarly low grades of concentrations of metal. The average vanadium ore mined in the United States in 1968 contained one percent vanadium metal. Beryllium ores, when they are mined at all in the United States, average about four percent beryllium in a silicate form.

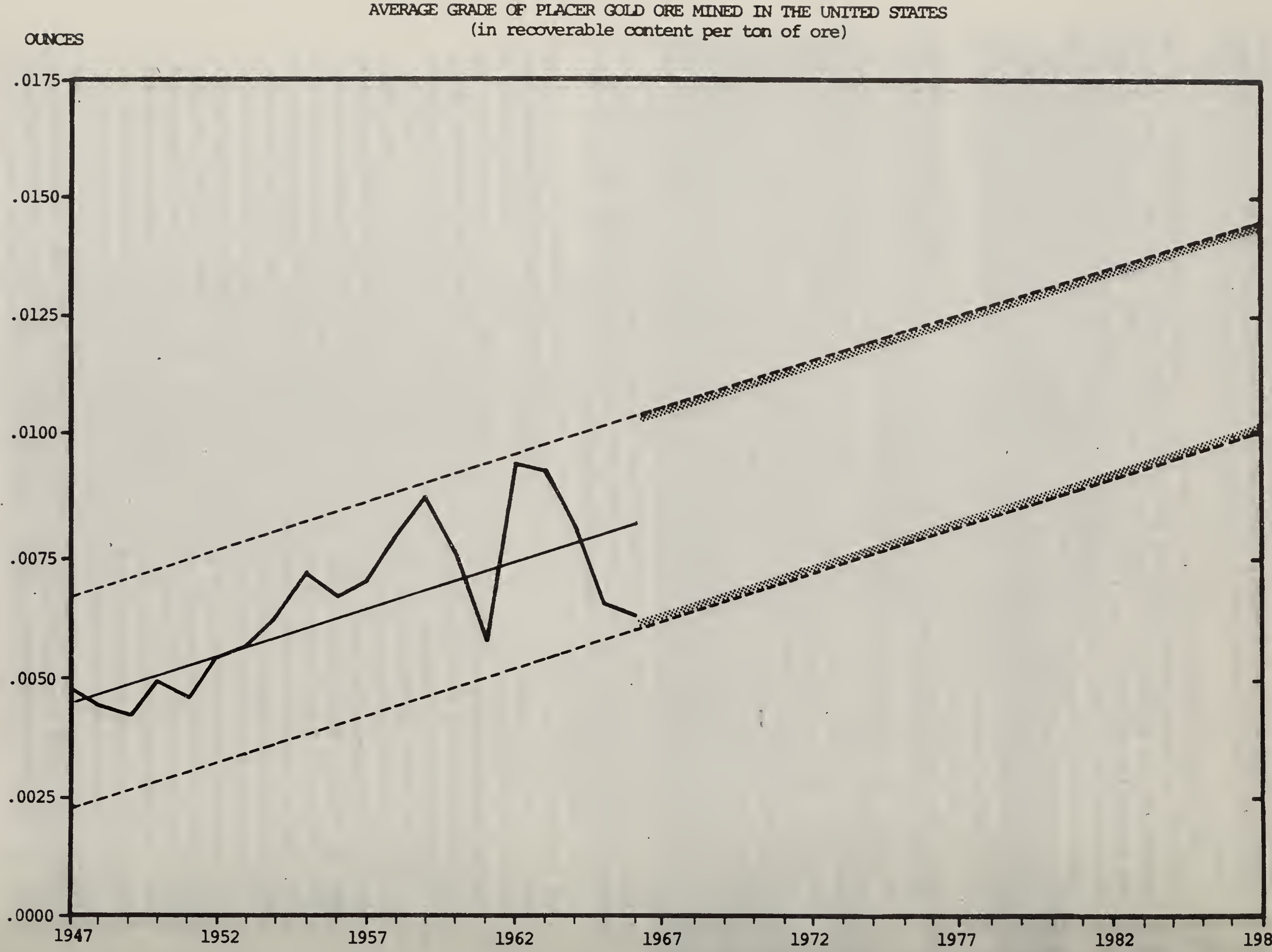


Fig. 42 - Average recoverable content of placer gold ore mined in the United States since 1947 with

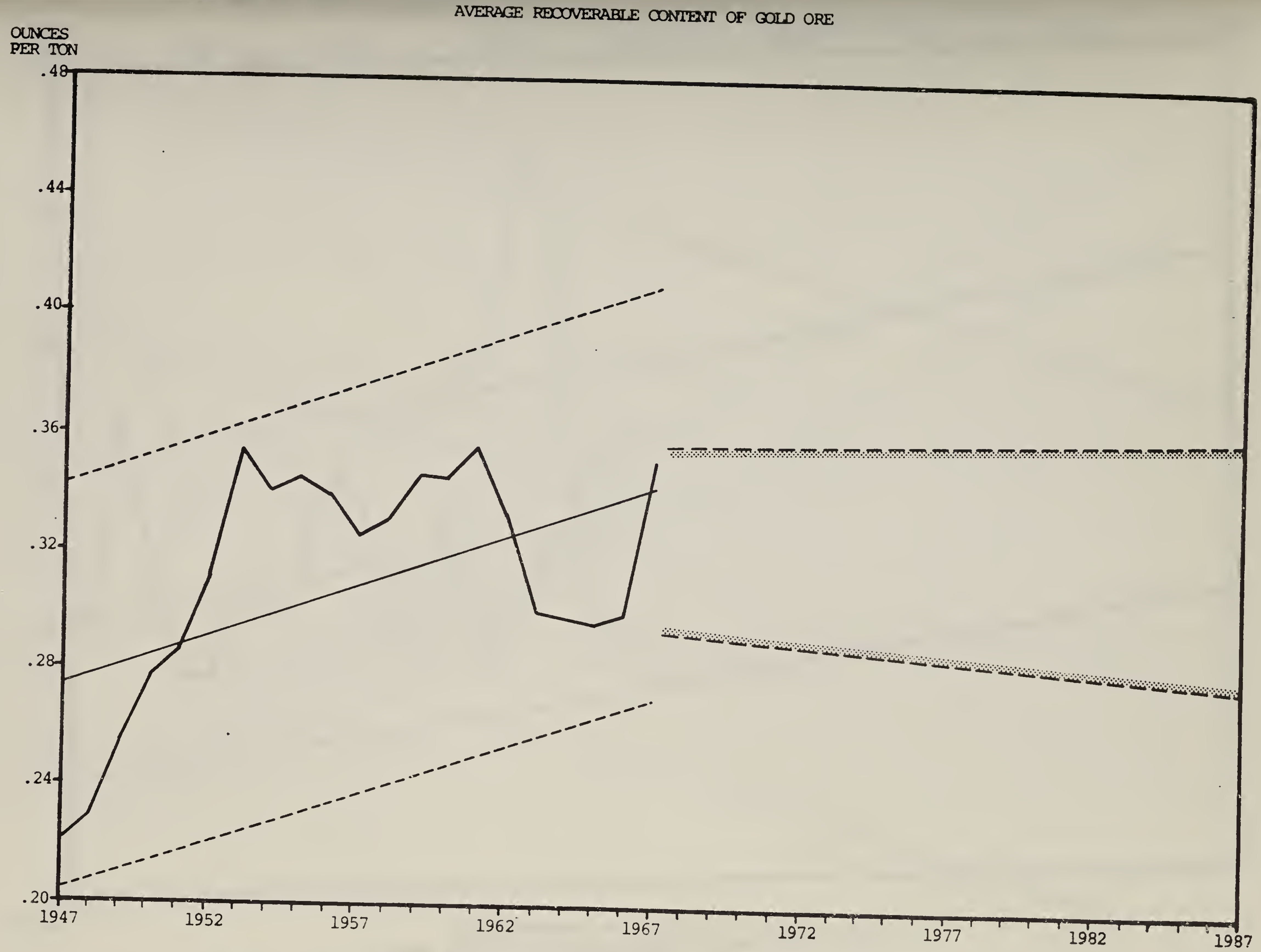
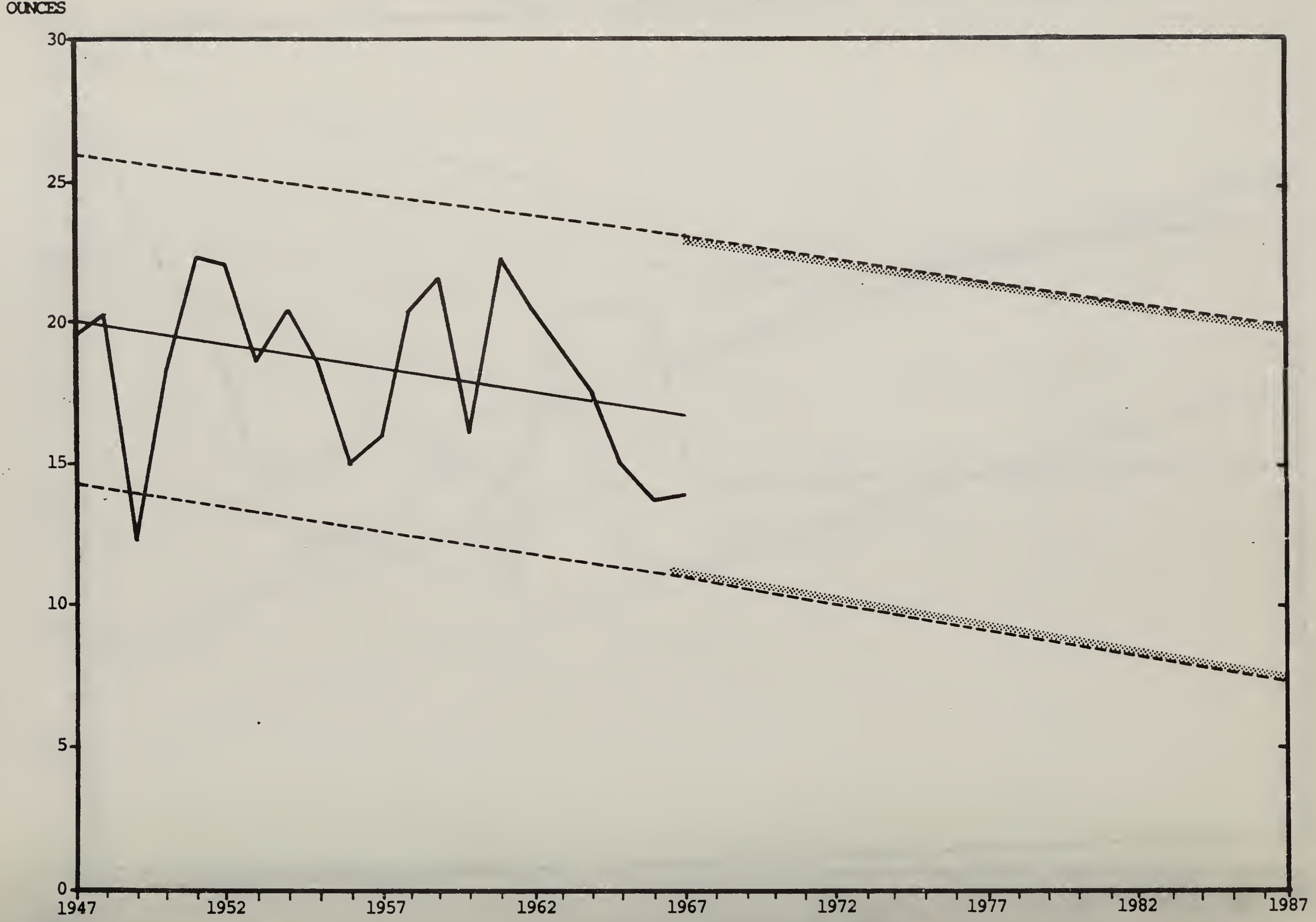


Fig. 43 - Average recoverable content of non-placer gold ore mined in the United States since 1947 with projection of trend from 1952 to 1967 forward to 1985.



AVERAGE GRADE OF SILVER ORE MINED IN THE UNITED STATES
(in recoverable content per ton of ore)

Fig. 44 - Average recoverable content of silver ore mined in the United

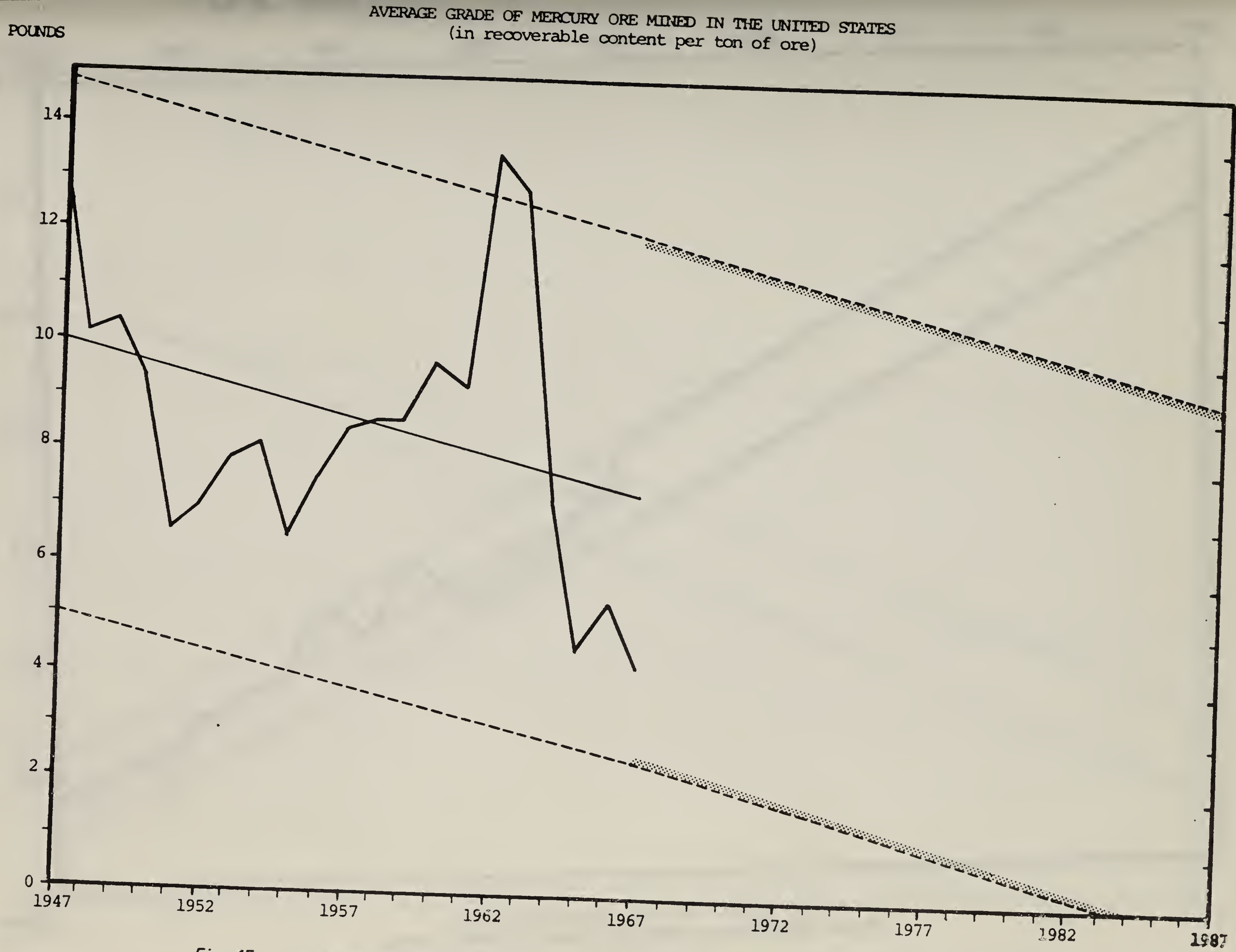


Fig. 45 - Average recoverable content of mercury ore mined in the United States since 1947 and projected to 1985.

AVERAGE GRADE OF COPPER ORE MINED IN THE UNITED STATES
(in recoverable content per ton of ore)

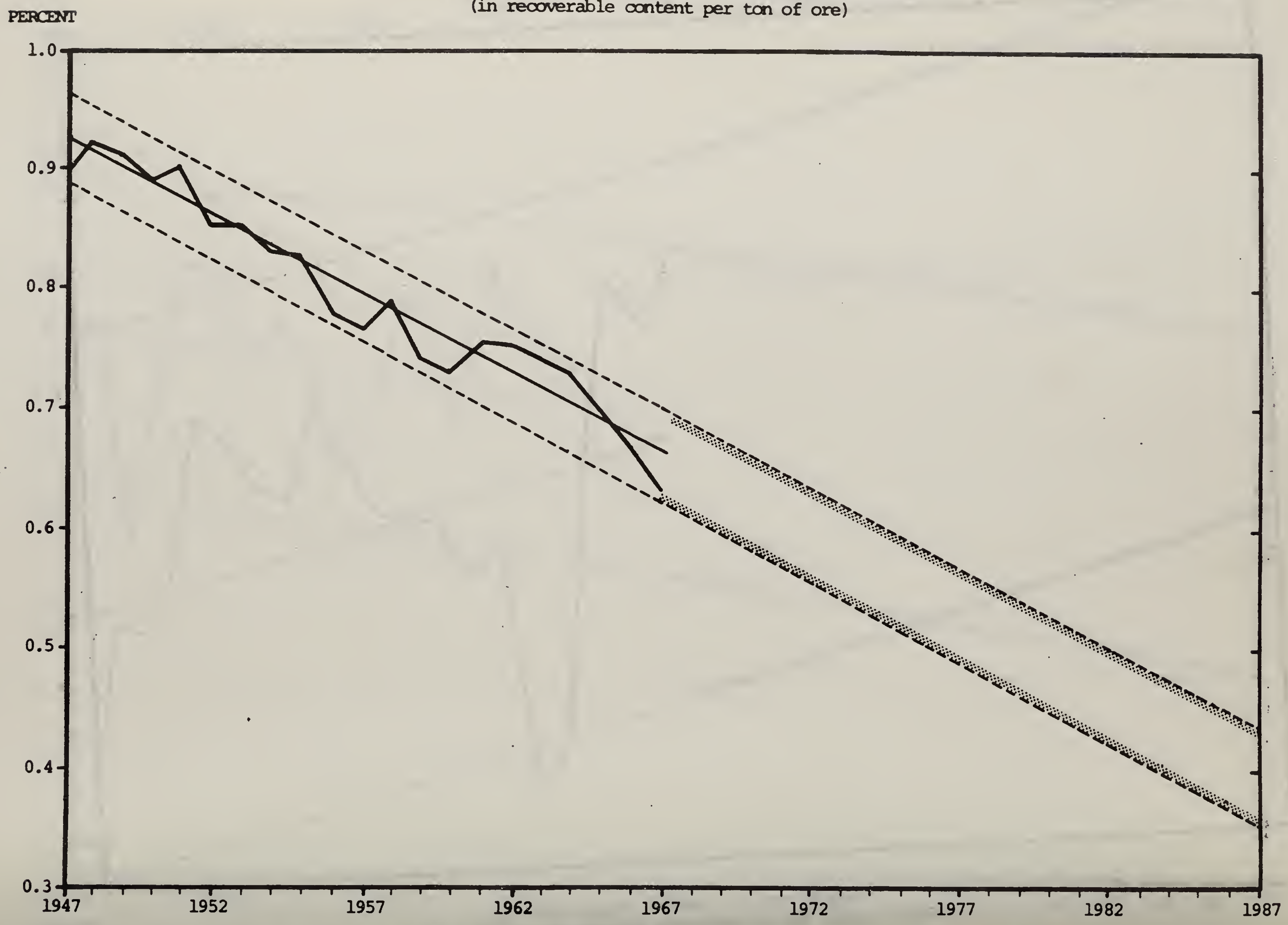


Fig. 46 - Average recoverable content of copper ores mined in the United States since 1947 and

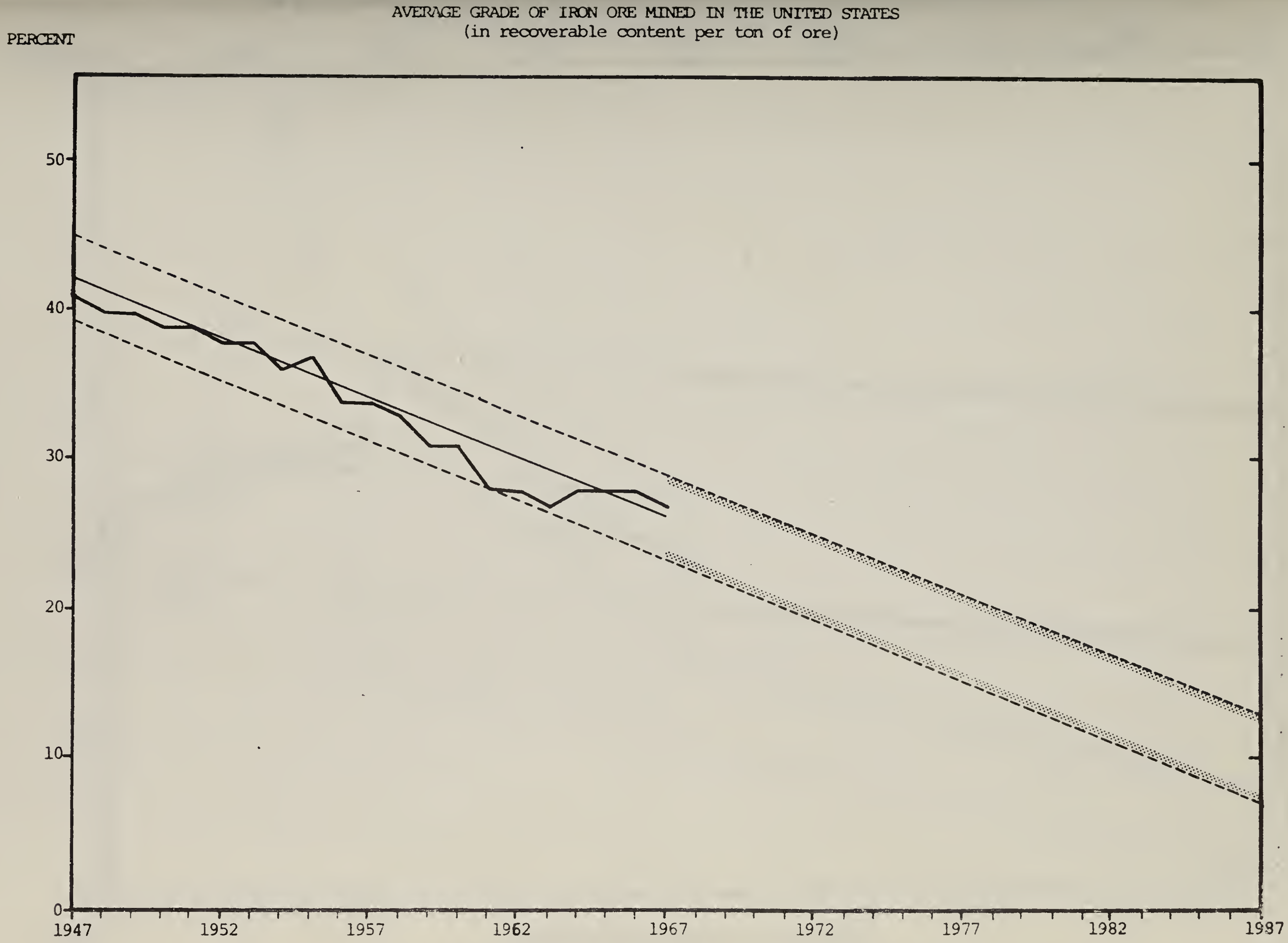


Fig. 47 - Average recoverable content of iron ores mined in the United States since 1947 and projected to 1985.

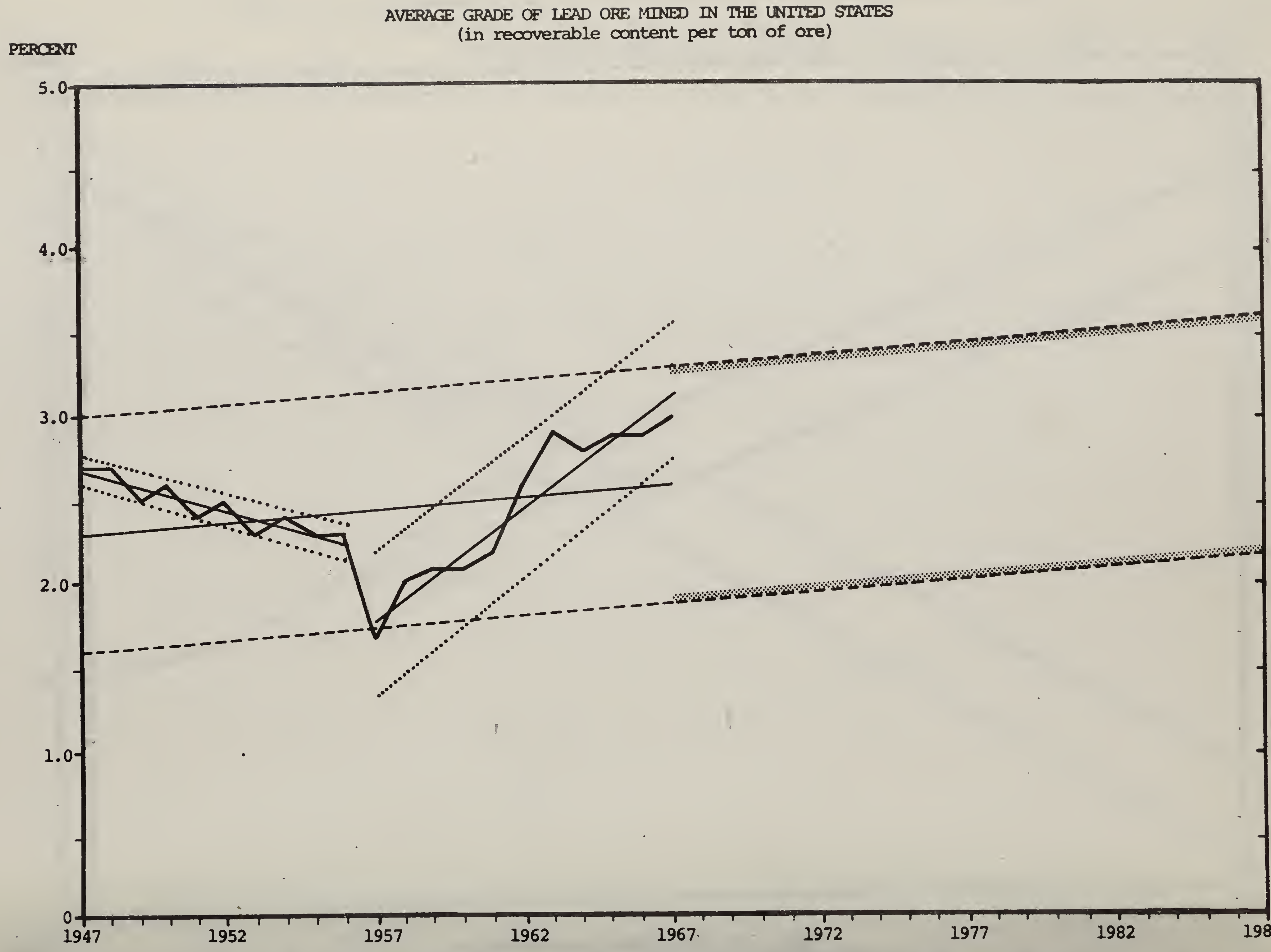


Fig. 48 · Average recoverable content of lead ores mined in the United States since 1947 and projected to 1985, including only those ores mined primarily for their lead content.

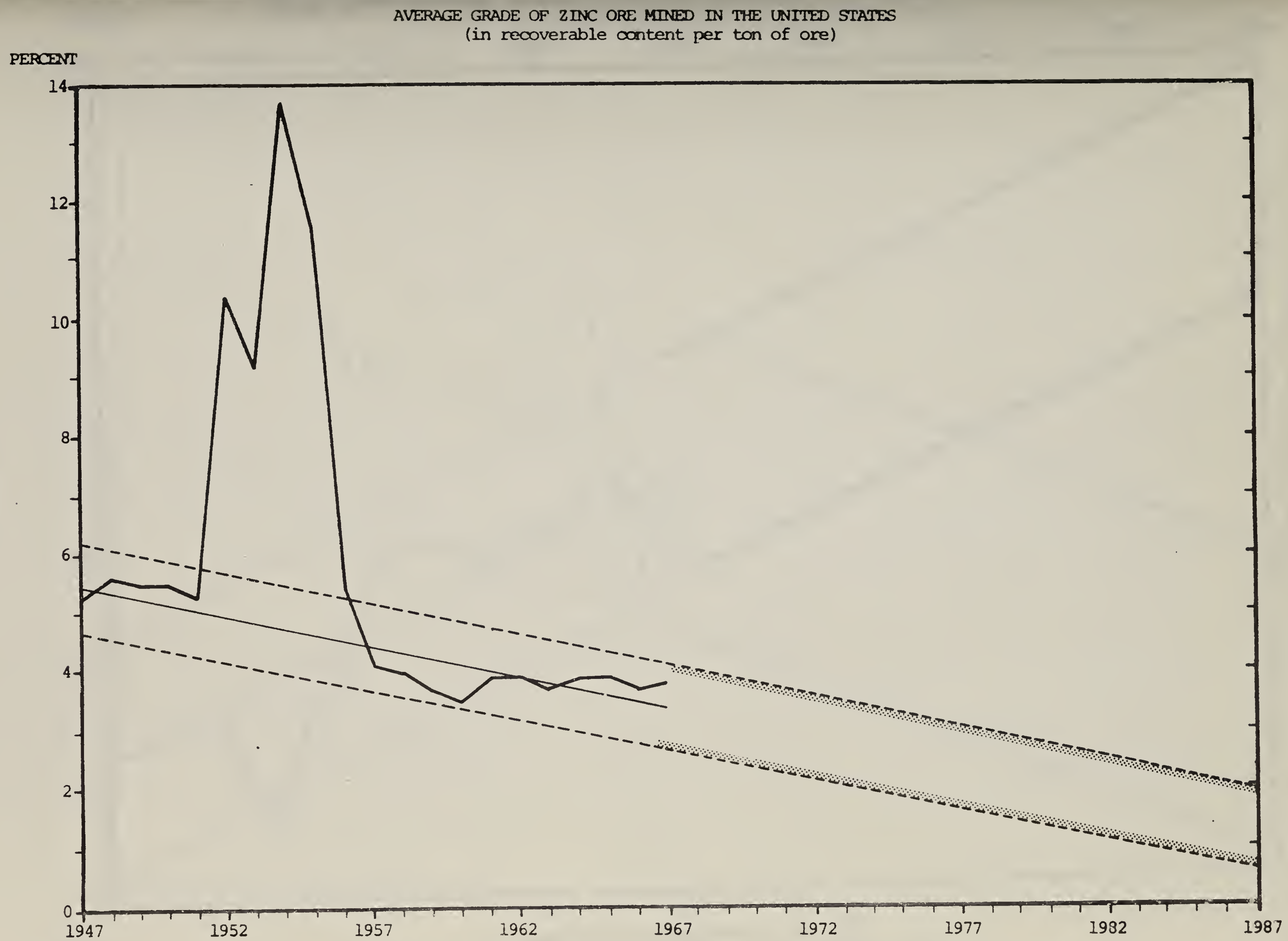

AVERAGE GRADE OF ZINC ORE MINED IN THE UNITED STATES
(in recoverable content per ton of ore)

Fig. 49 - Average recoverable content of zinc ores mined in the United States since 1947 and projected to 1985, including only those ores mined primarily for their zinc content.

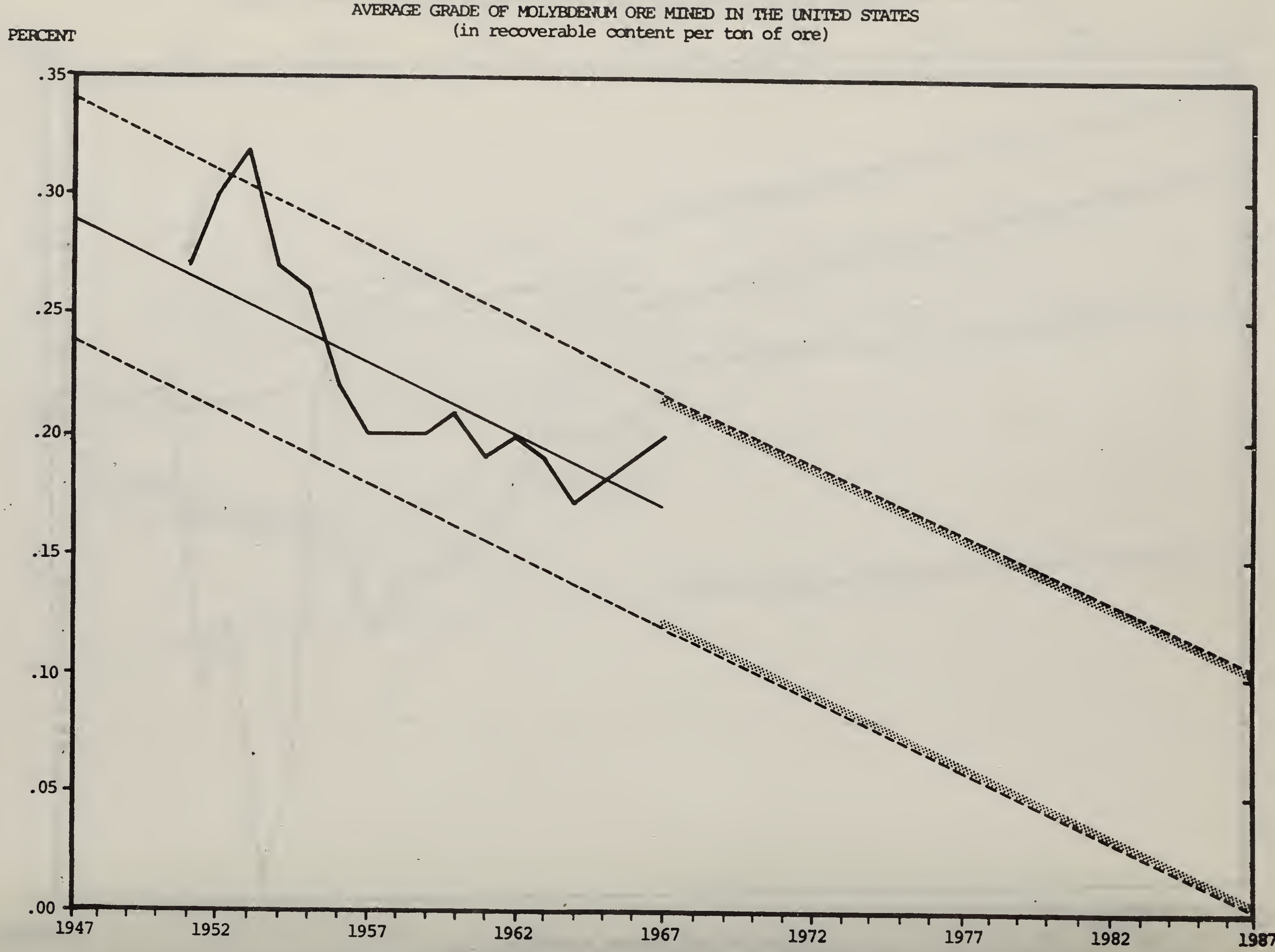


Fig. 50 - Average recoverable content of molybdenum ore mined in the United States since 1947 and projected to 1985, including

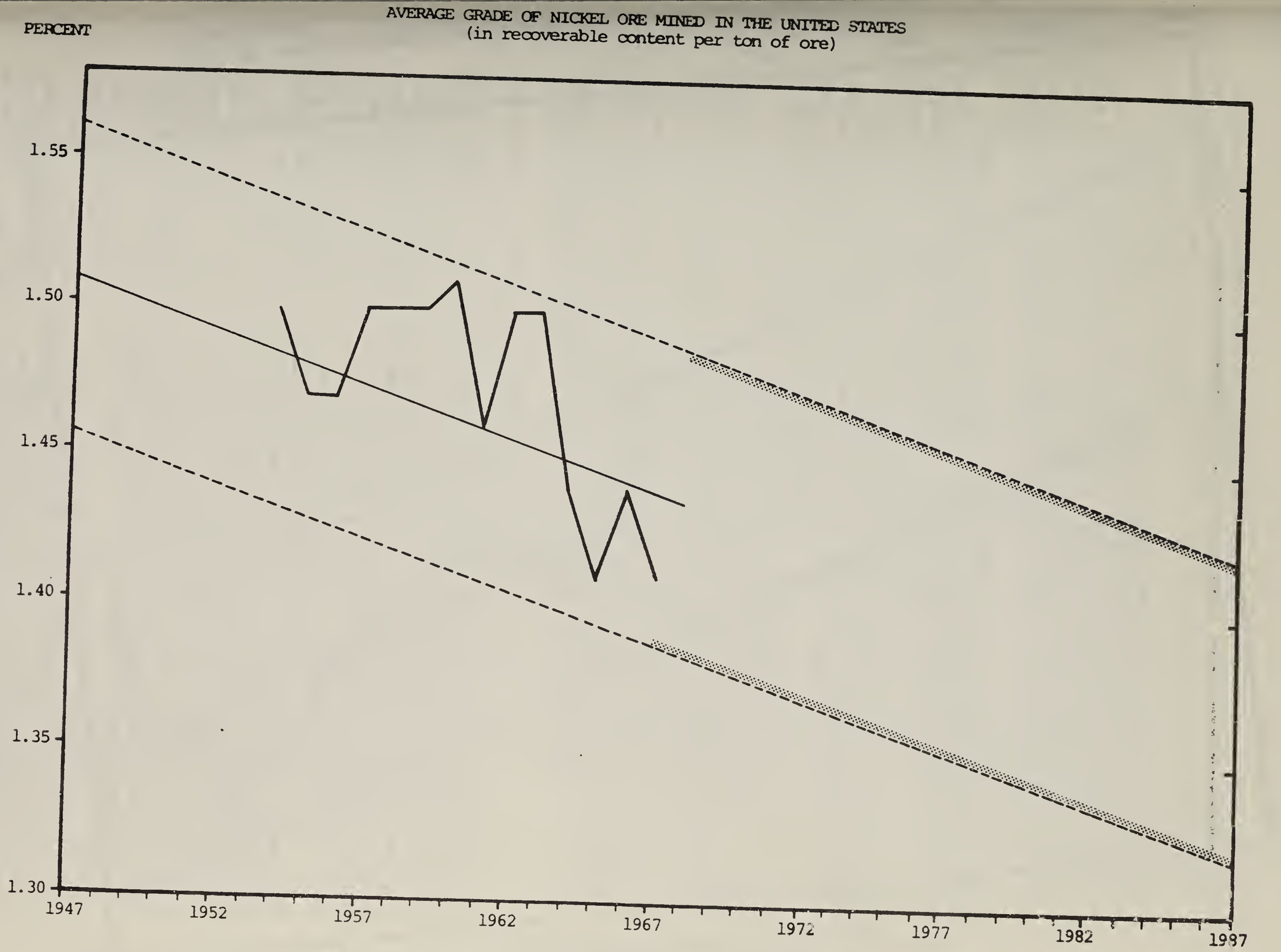


Fig. 51 - Average recoverable content of primary nickel ore mined in the United States and projected to 1985.

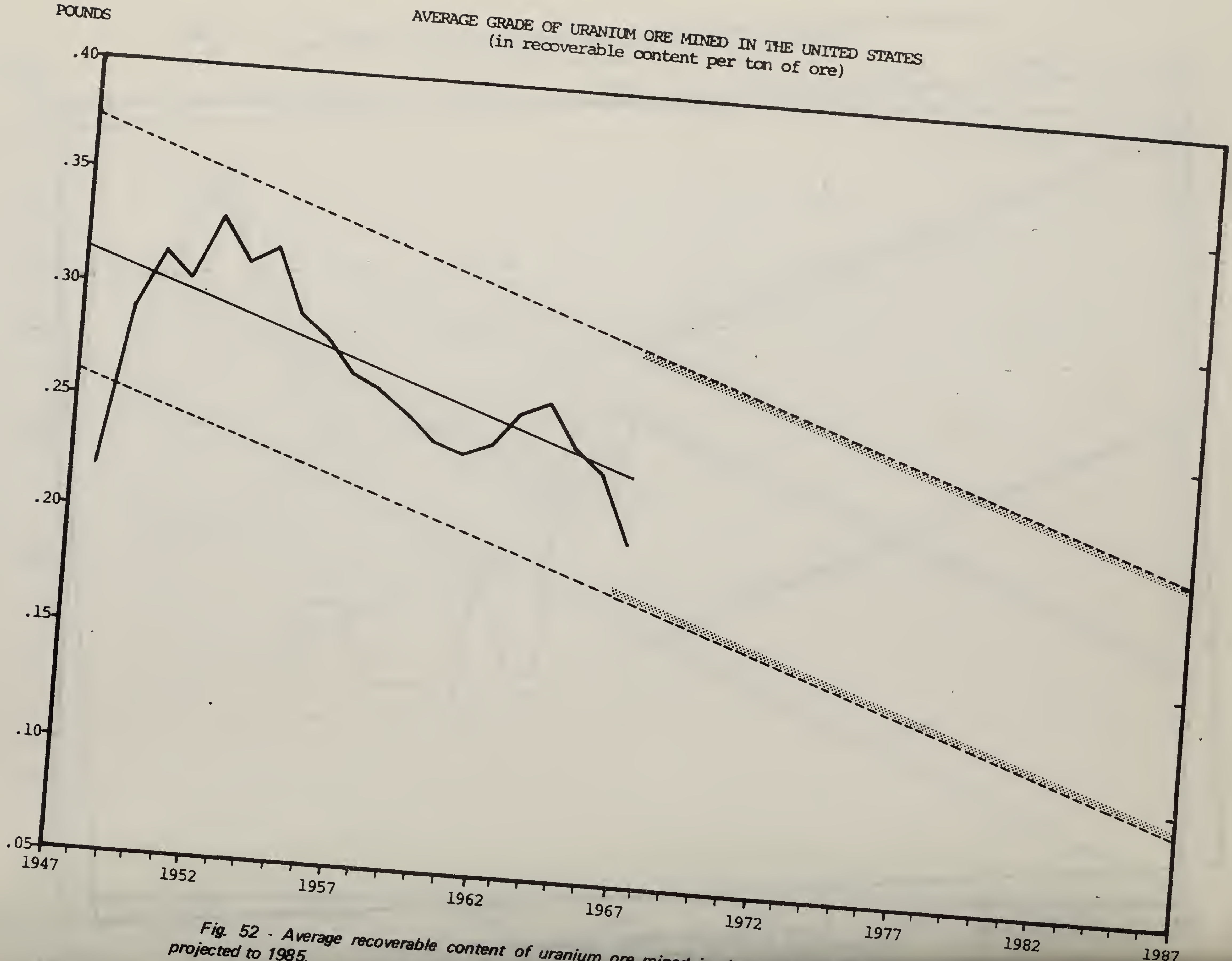


*Fig. 52 - Average recoverable content of uranium ore mined in the United States since
projected to 1985.*

Tungsten ores averaged about 0.4 percent with the tungsten in the oxide form. Manganese ores were the major exception to the relatively low grades found in ores of alloying metals. Where they are mined at all (and this is rare in the United States at present) manganese ores average about 35 percent manganese.

Among the industrial minerals, the grades of commercial rock mined in some instances were similar to those that had been mined in the past. In other instances they had changed. The average grades of limestone mined (in terms of calcium in carbonate form) remained relatively unchanged in 1968 from 1860. In hydrated sulphate form, however (i.e., as gypsum), the average grade of rock mined contained about 21 percent calcium in hydrated sulphate form. This, although different from the 1860's, was relatively unchanged from 1947.

Potassium, where mined as a solid rock, contained about 15 percent potassium in the oxide form in 1968. Where found in brines containing potassium oxides, the average deposit contained about two percent potassium. The average grade of sulfur deposits mined in the United States in 1968 ranged from 20 percent to 40 percent contained sulfur. Like potassium, this also was relatively unchanged from 1947.

Sodium was mined in 1967 in several forms. In the chloride form, i.e., as rock salt, the average grade of deposit still contained about 39 percent sodium. Sodium carbonate deposits mined in the late 1960's contained about 22 percent sodium in the carbonate form. Most of these were produced from trona deposits.

The average recoverable content of phosphate rock deposits mined in the United States has increased since 1947. The grade of commercially useable phosphate deposits remained constant for many years at 12 percent, with exceptions in only two years (1953 and 1954) when the average content rose to 13 percent P_2O_5. In 1959, the average grade of phosphate rock mined in the United States increased to 15 percent and subsequently to 16 and then to 17 percent. From a high of 17 percent P_2O_5 in 1965, the average valuable content of phosphate rock mined in the United States has dropped, however, falling to 15 percent in 1967. It should be noted, however, that these represent averages of the several grades of phosphate rock normally mined in the United States and which are used for different purposes. Useable grades actually range from six percent to 16 percent P_2O_5.

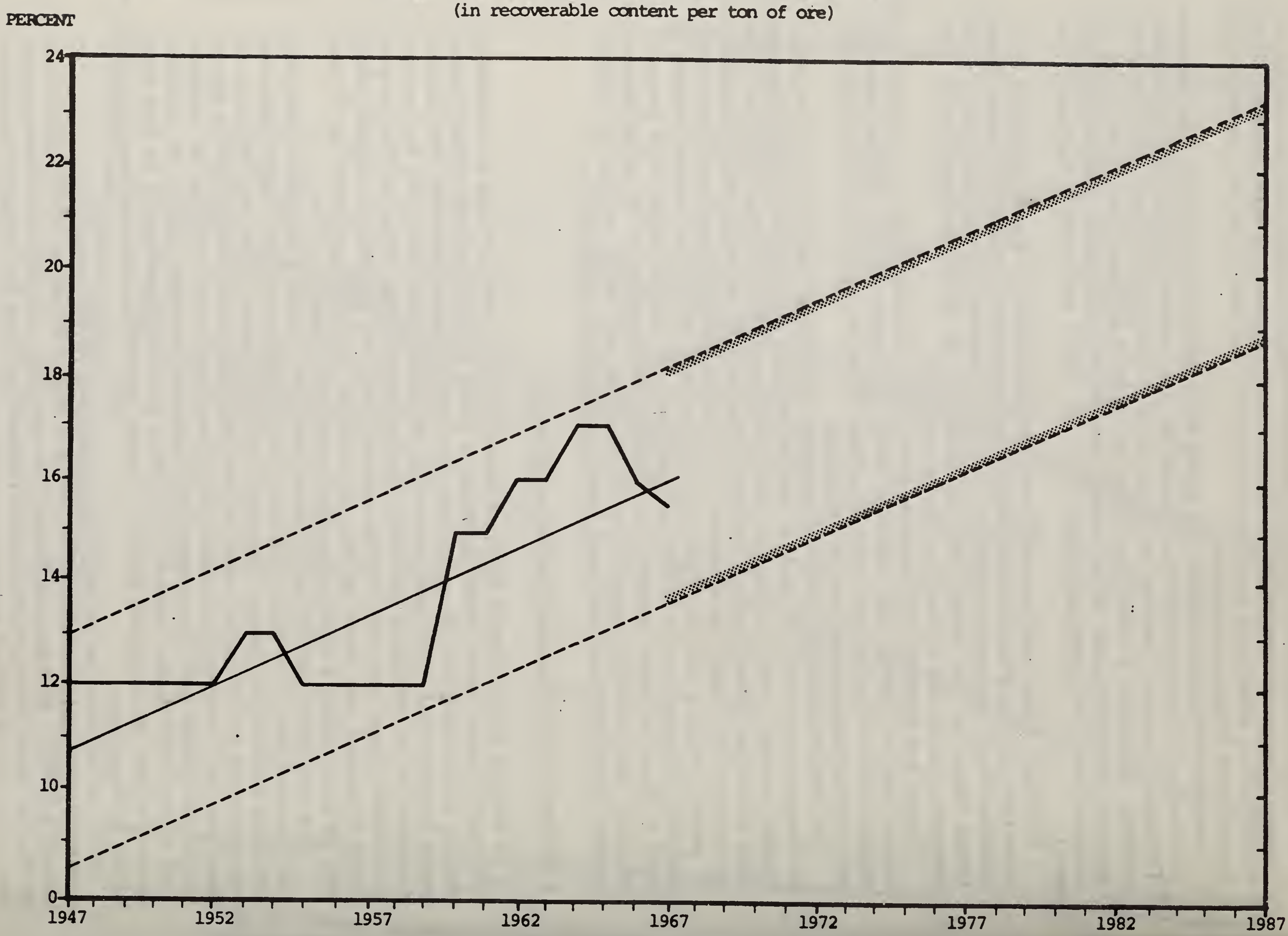
4. Changes in the Importance of By-Product Minerals

In addition to the changing grades of mineral deposits, there have also been changes in the relative proportions of metals produced as co- or by-products from complex mineral deposits as contrasted with the proportions produced as principal products from relatively simple deposits. Much of the gold produced in the United States since 1947 has been as a by-product in the refining of base metal ores, principally those of copper. The low-grade disseminated copper ores from Bingham Canyon, Utah, have accounted for a major portion of the by-product gold which has been so produced, and Bingham Canyon has for years been the second largest gold-producing mine in the United States.

The percentage of domestic gold produced in any one year as a by-product of base metal ores has varied from 28 to 40 percent since 1947. During most of this time, the percentage has ranged from 35 to 40 percent. The effect on gold production of the labor walkout in the copper industry and low copper prices and reduced production in 1958 and 1959 is evident. (See Figure 54.) Increased production from disseminated copper ores and the closing of most of the straight gold mines brought the by-product percentage up from 29 percent in 1947 to the 35-40 percent range by 1951, where it has remained most of the time since. Production from the Carlin gold deposit in Nevada has kept the percentage from increasing further in recent years.

Silver, derived from ore in which it is the principal product, ranged from a low of 17 percent of total domestic production in 1949 to a high of 42 percent in 1959. Most of the nation's by-product silver has been derived from disseminated copper and lead-zinc mines in the Western United States. A small portion (generally less than five percent) of by-product silver is derived from gold and gold-silver (in which silver is a co-product) ores.

AVERAGE GRADE OF PHOSPHATE ORE MINED IN THE UNITED STATES
(in recoverable content per ton of ore)



in the United States since 1947 and projected to 1986.

Fluctuations in the percentage of by-product silver have been due in large part to conditions in the base metal industries. Labor disputes and periods of low base metal prices have caused the by-product percentage of silver to decrease sharply in some years. On the average, the percentage of silver produced from ore in which it is the primary product has been increasing since 1947. New base metal deposits containing minor amounts of silver which have come into production since 1959, however, have contributed to the declining primary product trend from 1959 to 1966.

Small amounts of *molybdenum* minerals are present in most disseminated copper ores. Prior to 1947, only a few copper mines had molybdenum recovery circuits in their concentrating plants. Since then, however, molybdenum sulfide recovery circuits have been installed at nearly all of the disseminated copper mines. Some molybdenum has been recovered as a by-product from tungsten and uranium ores, but by far the largest source of by-product molybdenum has been the disseminated copper deposits.

From 1947 to 1966, the two largest deposits yielding molybdenum in the United States were Climax, Colorado (disseminated low-grade molybdenum sulfide), and Bingham Canyon, Utah (disseminated low-grade copper ore, with small amounts of molybdenum). The amount of molybdenum produced as a by-product exceeded 50 percent of total domestic production in 1947, 1949, and 1950, principally because of the large volume of output from Bingham Canyon. Climax, the nation's largest primary producer, subsequently expanded its output, thus decreasing the by-product percentage. Since 1955, the amount of molybdenum recovered as a by-product from ores of other metals has ranged mostly from 27 to 38 percent. Fluctuations in the by-product percentage have reflected changes in the rate of production at Climax as well as the steadily increasing number of recovery circuit installations at both new and old (prior to 1947) disseminated copper deposits.

The disseminated molybdenum deposit at Questa, New Mexico, and Climax's plant for recovery of molybdenum from oxide ores came into production in 1966, adding an estimated 13 million pounds to primary production capacity. In 1966, total domestic production was approximately 92 million pounds of molybdenum. The Urad, Colorado, deposit, also owned by Climax Molybdenum Company, was brought on-stream in mid-1967, thus decreasing the importance of by-product molybdenum.

Antimony produced from ore in which it is the primary constituent has decreased from a high of 45 percent of total smelter production in 1948 to six percent in 1966. More than half of the antimony refined (excluding reprocessed scrap) in the United States since 1961 has been from foreign ores. The largest source of domestic antimony is from antimonial lead ores. The price of antimony has been too low, and the grade of most domestic antimony deposits too low, to allow more than scattered small production of the metal from deposits in which it is the primary constituent.

Arsenic is, and has been since 1947, produced entirely as a by-product from the smelting of both domestic and foreign base and precious metal ores. The value of arsenic is extremely low and it is usually considered a contaminant which must be eliminated from other metals during their refining, so that it is not always recovered from domestic ores. Most of the domestic smelter production of arsenic in recent years has been from foreign ores.

Imports of arsenic compounds increased from slightly more than 50 percent of total production in 1948 to more than 90 percent in 1959. Since 1959, only one United States smelter has produced arsenic for sale, and data on domestic arsenic production have been withheld.

In the United States, bismuth has been recovered almost exclusively as a by-product in the smelting of base and precious metal ores (principally lead and lead-silver ores) from the Western United States. Approximately 50 percent of domestic bismuth requirements are imported, however. Bismuth constitutes a very small percentage of the total metal content of ores from which it is extracted.

All of the domestic cobalt production since 1947 has been as a by-product in the refining of ores of other metals, principally iron, except for the period from 1951 to 1959 when the Blackbird Cobalt deposit in Idaho was under production. During its period of

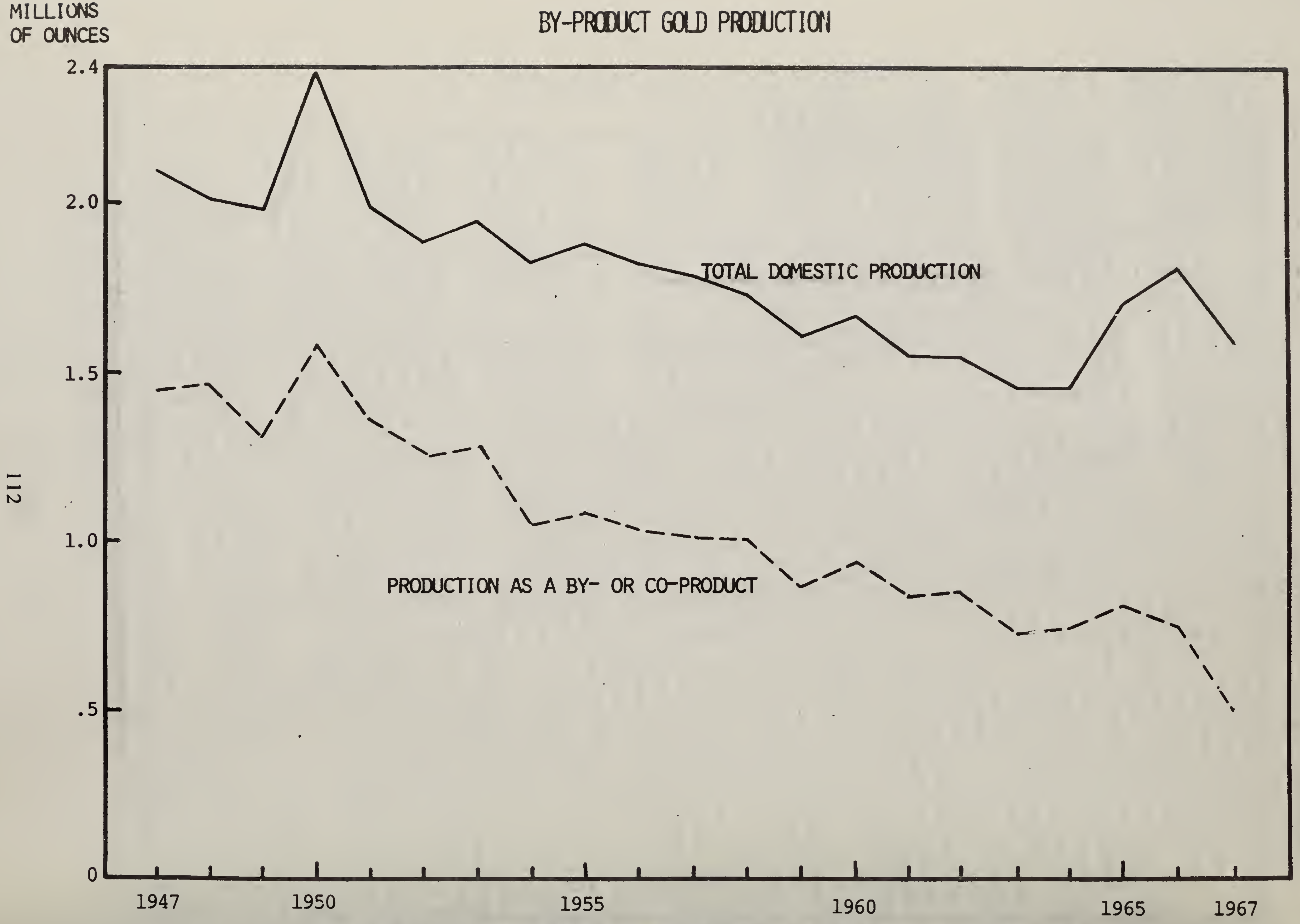


Fig. 54 - Proportion of gold production in the United States since 1947 as a by- or co-product in the production of other minerals. Recent developments of large, near-surface disseminated deposits in Nevada have increased the importance of primary gold.

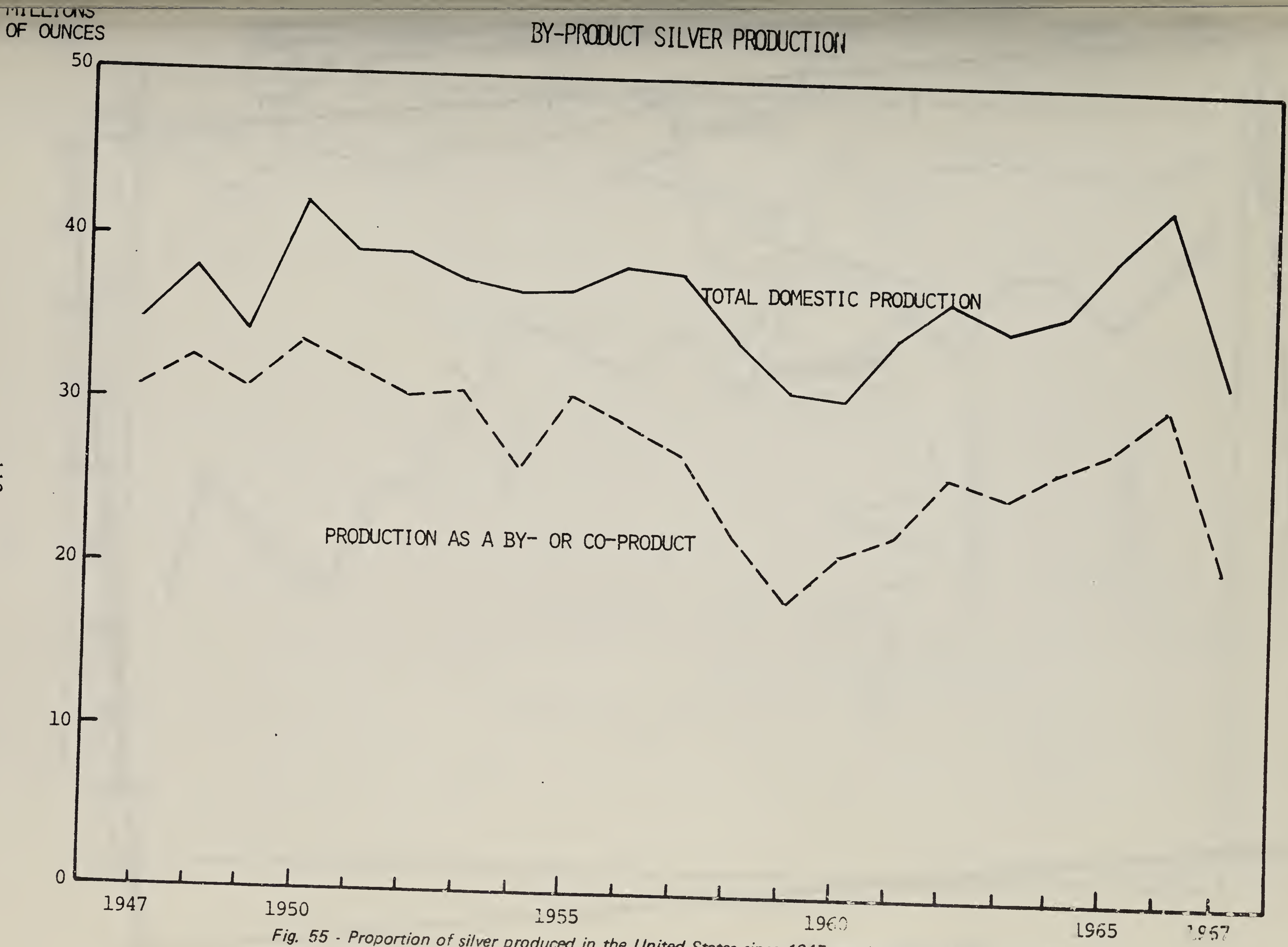


Fig. 55 - Proportion of silver produced in the United States since 1947 as a by- or co-product in the production of other minerals. Rising silver prices over the past two decades have increased the importance of primary silver only gradually.

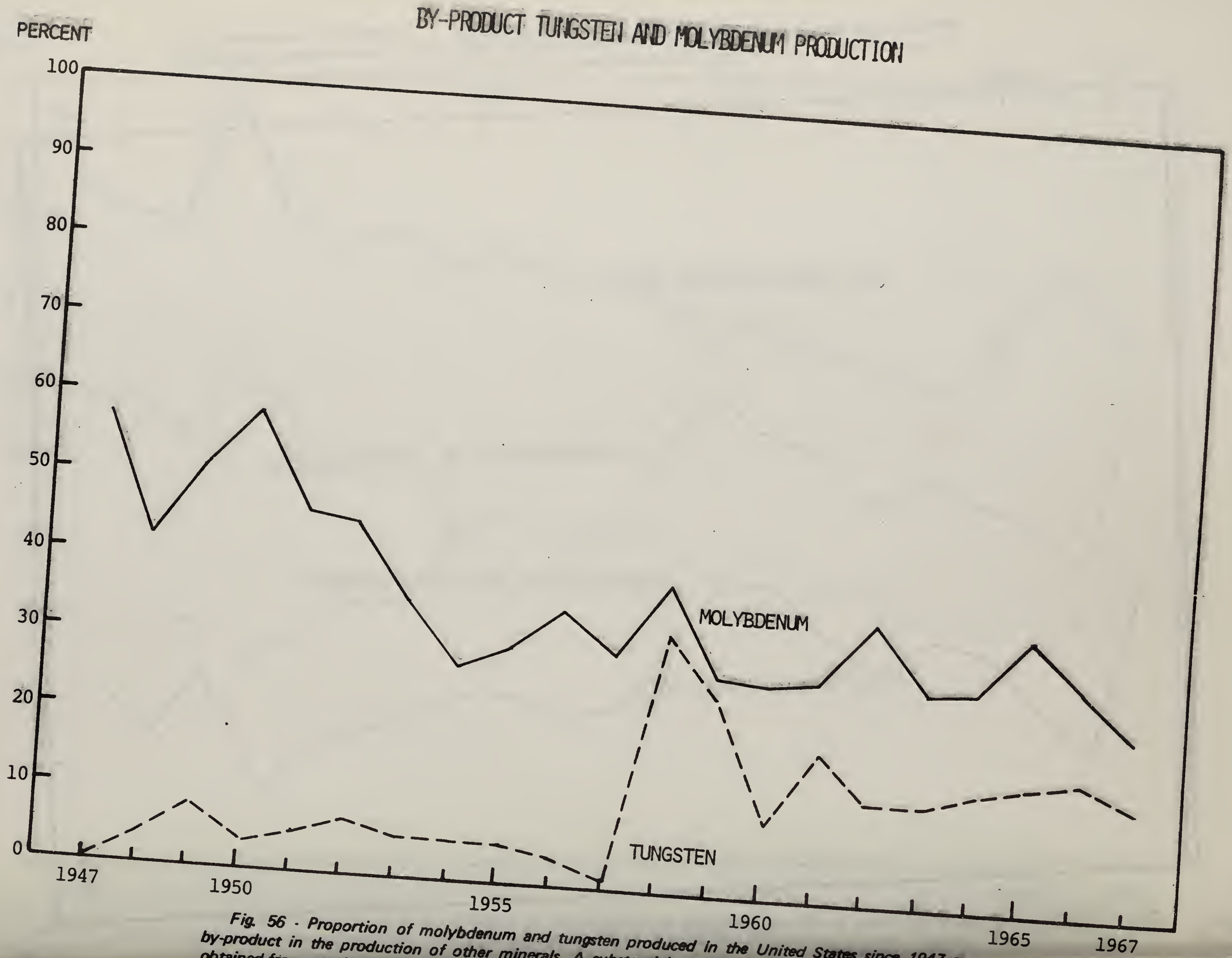


Fig. 56 - Proportion of molybdenum and tungsten produced in the United States since 1947 by-product in the production of other minerals. A substantial obtained from ores in which

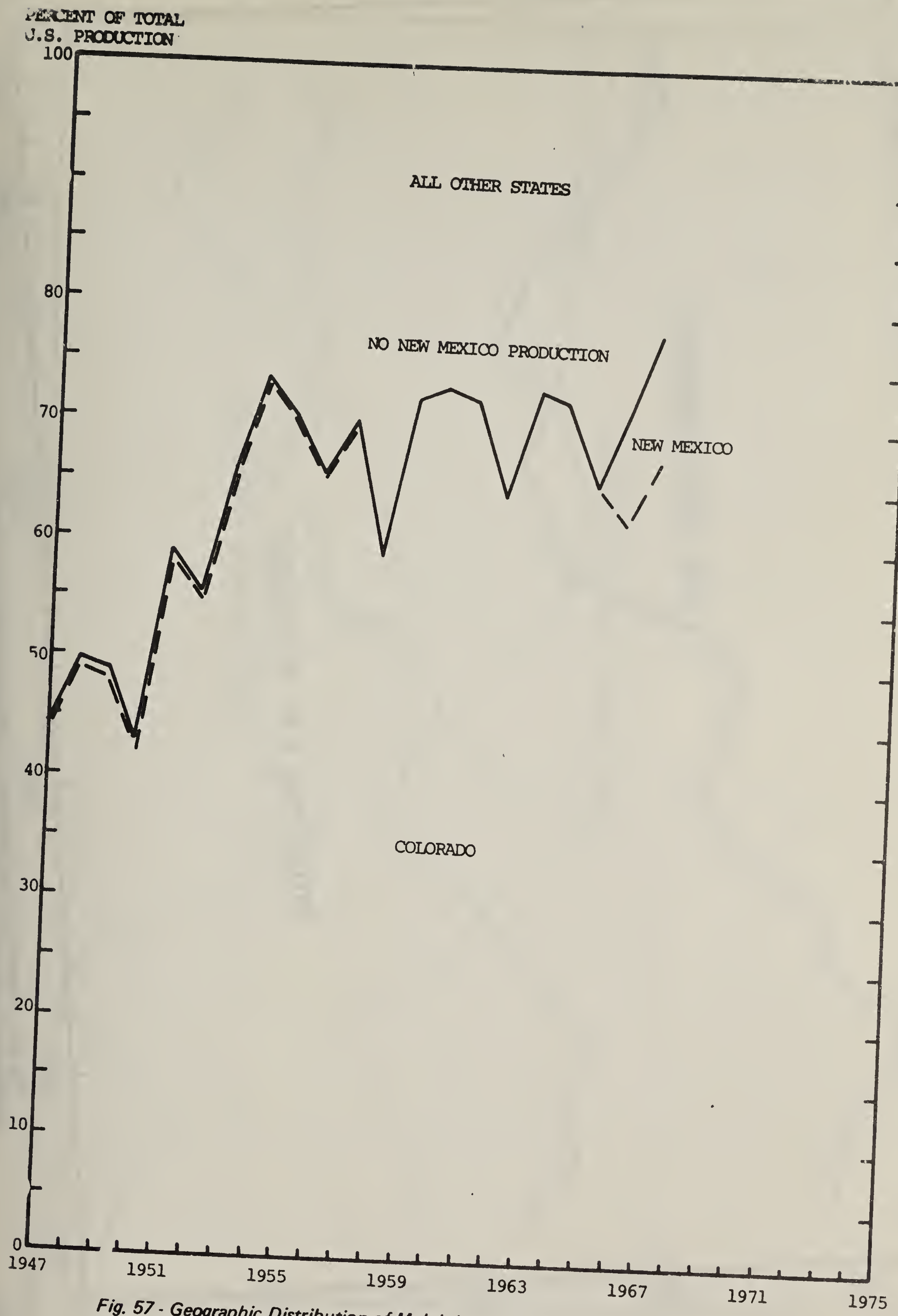


Fig. 57 - Geographic Distribution of Molybdenum Production in the United States.

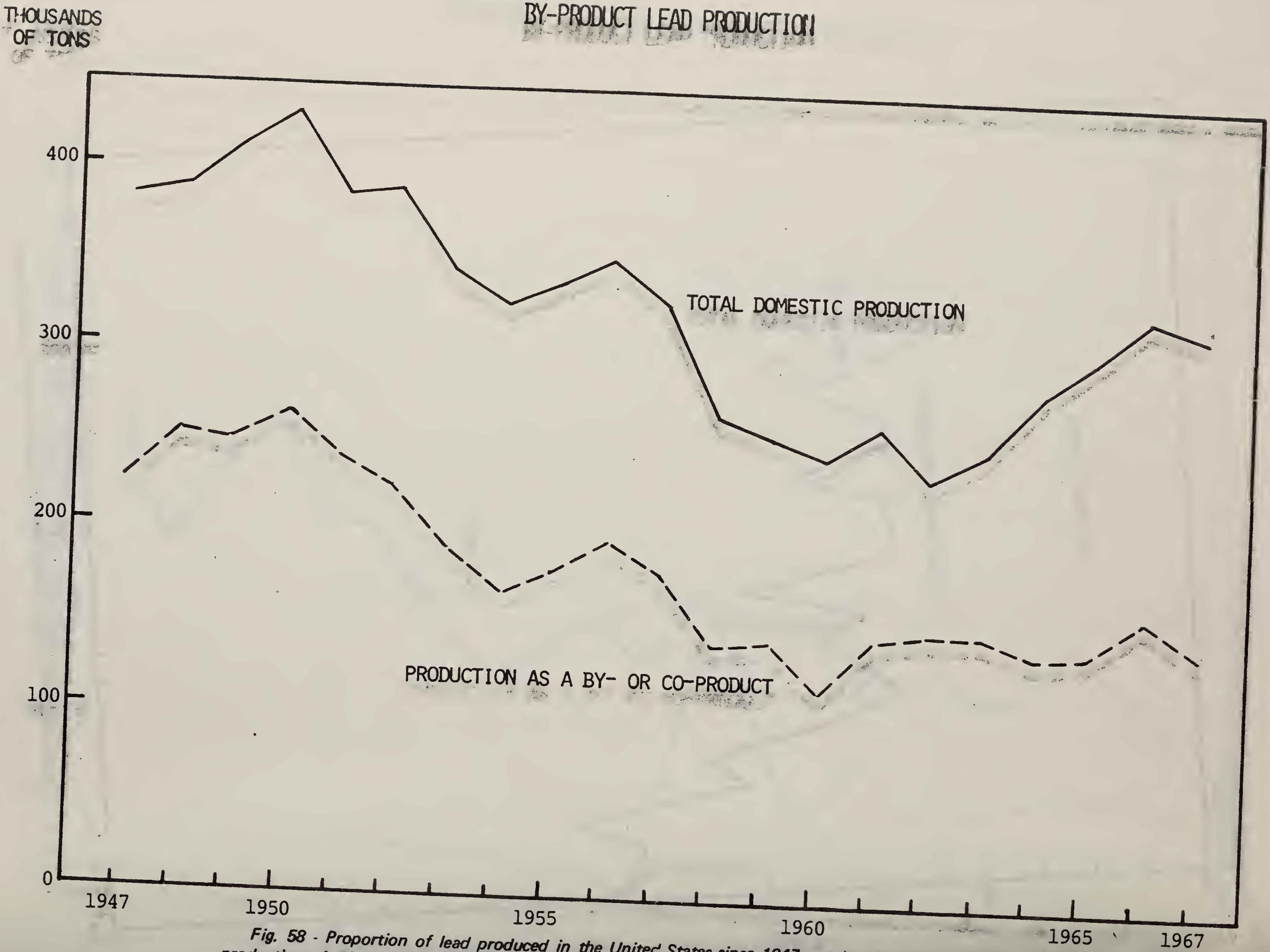


Fig. 58 - Proportion of lead produced in the United States since 1947 as a by- or co-product in the production of other minerals. The recent development of newly discovered deposits in Missouri has raised the importance of ores mined principally for their lead content

BY-PRODUCT ZINC PRODUCTION

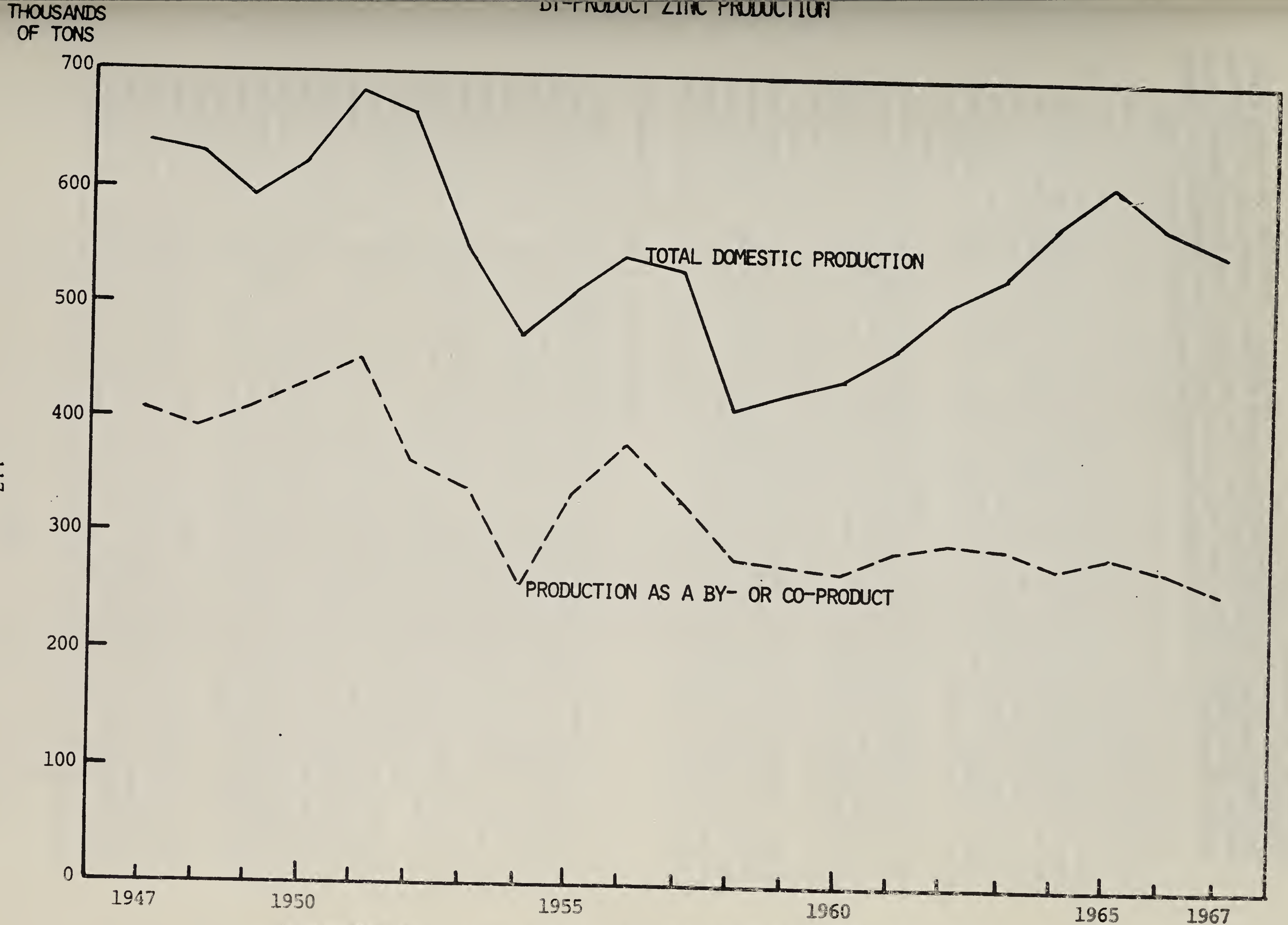


Fig. 59 - Proportion of zinc produced in the United States since 1947 as a by- or co-product in the production of other minerals. New developments in the early 1960's increased the importance of primary zinc ores.

operation, the Blackbird Mine was the major producer of cobalt in the United States. Competition from foreign sources, however, forced the mine to close down in 1959. Some lead, nickel, and copper ores in Missouri and Idaho also contain cobalt and have been minor sources of the metal. Most of the domestic demand for cobalt is supplied from foreign sources. From 1963 to 1966, 45 percent of the imported cobalt came from the Congo.

D. KNOWN MINERAL RESOURCES IN 1968

1. Metallic Mineral Reserve Estimates

Most of the nation's presently known metallic mineral resources are situated in the Western United States (Figure 60). Table 8 lists, by metal, those states in which the principal known metallic mineral deposits (and production) occur. Table 9 lists recent ore reserve estimates for the major metals and some of the non-metallic minerals. These estimates, however, include assumptions of ore which have not been proven. Proven reserves constitute less than half of the quoted figures and probably less than one-quarter for some mineral commodities (e.g., mercury). Current data do not distinguish between *proven*, *indicated*, and *inferred* reserves, but some previous estimates have given a measure of the unproven portion of present reserve estimates for some metals. Tungsten reserves, particularly, include a large portion of rock which is not ore under present economic conditions.

Proven reserves which are *responsive* to changes in demand (i.e., not as contained metals extracted as by-products of the mining of other ores) constitute less than 10 percent of the quoted figures. A significant percentage (30 to 40 percent) of molybdenum is produced as a by-product from copper ores, and responsive reserves of molybdenum are thus less than the figures shown. When the quoted reserve figures are reduced to proven, responsive, useful reserves, they may not be as adequate as Table 9 would imply.

Known reserves and production of molybdenum, gold, silver, mercury, tungsten, nickel, and uranium are almost exclusively restricted to the Western States. Most of the nation's known copper reserves are also in the West. A large proportion of lead and zinc reserves and production are also supplied by western states. Western iron ore reserves, although presently small in comparison to those of known eastern deposits, provide a large portion of western iron and steel industry requirements.

2. Industrial Minerals Reserve Estimates

Many non-metallic mineral resources, such as sand and gravel and limestone, are widely though not uniformly distributed over the United States. The quality of these deposits and their suitability for specific uses governs their value as mineral resources. Large portions of the Southeastern United States lack deposits of these mineral commodities, which are brought in from hundreds of miles away. Most of the industrial minerals centers of production and consumption are in the eastern half of the United States, which is more heavily populated and more heavily industrialized than the western half. Known economic deposits, and potentially known economic resources, of some industrial minerals are preferentially concentrated in restricted areas of the nation, as shown in Table 10.

The United States is presently self-sufficient in most of the industrial mineral commodities that command a high volume of consumption. On a local or regional basis, however, reserves are being depleted near consuming centers and new reserves must be found and developed at progressively greater distances from the market. Some industrial minerals (e.g., optical quartz, crystalline calcite, and mica) are almost exclusively imported and have been in critically short supply during wartime periods. Canada furnishes most of the asbestos used in the United States. Potash reserves in the United States are large, but of lower grade than those in Western Canada, which has taken an increasing share of the market in recent years.

Industrial minerals reserves are large and not fully explored or developed for most commodities. The rising population and urban industrial growth have stimulated demand, making many deposits previously uneconomic due to their distance from the market now economically exploitable. The development of new industrial uses and rising demand have also made ore bodies of some previously valueless deposits. For example, zeolites, used in chemical filtration, were thought to occur only in basalt and related rocks and then only in minor quantities. Exploration by Union Carbide, however, developed high-grade deposits associated with volcanic ash near Bowie, Arizona, and the ore now mined is valued at approximately two dollars a pound. Projected increases in market demand and the number of uses for zeolites will probably lower the unit price but create a much larger market.[131] The area containing these deposits was not previously known to contain any mineral deposits of present or future significant value. In a similar manner, new technology and uses will undoubtedly continue to develop, turning presently valueless rock and mineral deposits into the ore of the future.

Nearly all of the nation's known bentonite, potash, boron, sodium, perlite, and diatomaceous earth, and a substantial quantity of asbestos, phosphate, and gypsum reserves and production are in the Western States. Their full extent and quality are unknown.

Table 8

LOCATION OF PRINCIPAL ECONOMICALLY USEABLE DEPOSITS OF METALLIC MINERALS IN THE UNITED STATES

Metal	**Location**
Iron	1. Minnesota, Michigan, and Wisconsin 2. New York, New Jersey, and Pennsylvania 3. Alabama and Georgia 4. *Wyoming* 5. *California* 6. *Nevada* 7. *Colorado*
Copper	1. *Arizona, Utah, Nevada,* and *New Mexico* 2. *Montana* 3. Michigan
Lead	1. Missouri 2. *Idaho* 3. *Utah* 4. *Colorado*
Zinc	1. Tennessee 2. New York, *Idaho* 3. *Colorado* 4. *Utah* 5. New Jersey and Pennsylvania
Molybdenum	1. *Colorado* 2. *New Mexico* 3. *Utah* 4. *Arizona*
Gold	1. South Dakota 2. *Nevada* 3. *Utah* 4. *Arizona*

Table 8 (Continued)

Metal	**Location**
Silver	1. *Idaho* 2. *Arizona* 3. *Montana* 4. *Utah* 5. *Colorado*
Mercury	1. *California* 2. *Nevada, Oregon,* and *Idaho*
Tungsten	1. *California* 2. *Nevada, Colorado*
Nickel	1. *Oregon* 2. Minnesota
Uranium	1. *New Mexico, Utah, Colorado, Arizona* (Colorado Plateau) 2. *Wyoming*
Beryllium	1. *Utah*

The following metals are obtained almost exclusively from foreign sources:

Aluminum
Antimony
Chromium
Cobalt
Platinum
Tin
Beryllium
Manganese

States in *italics* are public land states.

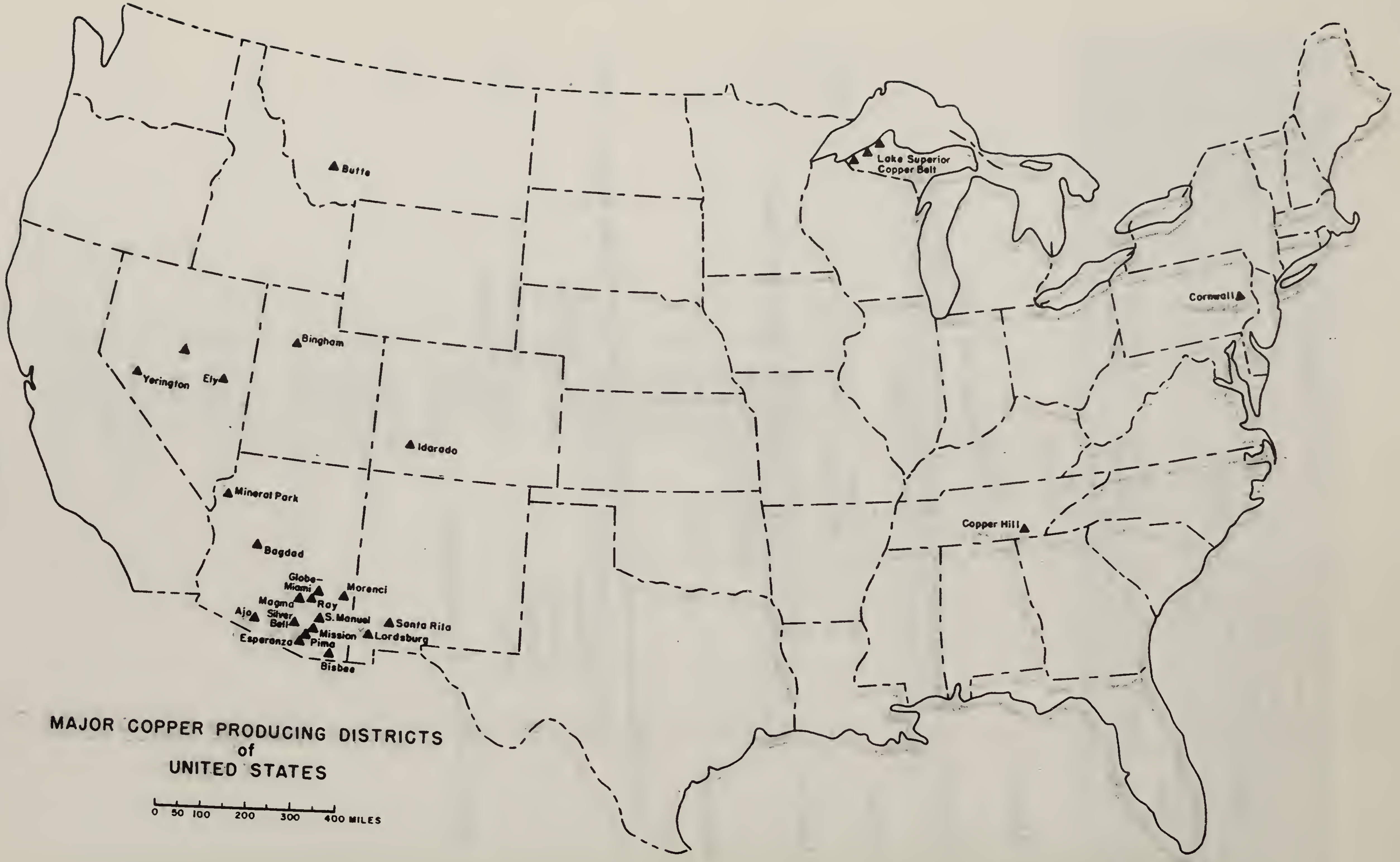


Fig. 60 – Major copper producing areas of the United States in 1968. The heavy concentration of such operations in the West is typical of the nation's nonferrous metal mining industry. Although favorable conditions for copper

Table 9

RECENT ESTIMATES OF RESERVES OF SOME MINERAL COMMODITIES

Iron Ore	15.0	billion long tons (25-60% iron content)
Copper	85.5	million short tons
Lead	35.0	million short tons
Zinc	15.0	million short tons
Silver	1,320	million troy ounces (including by-product silver ores)
Gold	54.0	million troy ounces (including by-product silver ores)
Mercury	825	thousand flasks (76 lb. each)
Tungsten	143	million pounds
Uranium	195	thousand short tons
Beryllium	600	thousand tons of Beryl (12.5% containing Beryllium oxide) minimum; principally in Utah deposits
Molybdenum	6,000	million pounds (including molybdenum produced as a by-product of copper ores)
Asbestos	5	million short tons (estimate, this report)
Nickel	1	million short tons
Potash	450	million short tons
Sodium Carbonate	650	million short tons minimum (U.S.B.M. Bull. 630, 1965)
Sodium Sulfate	261	million short tons minimum
Fluorspar	5.1	million short tons

Source of Data: *Commodity Data Summaries*, January, 1965, U.S. Bureau of Mines.

Table 10

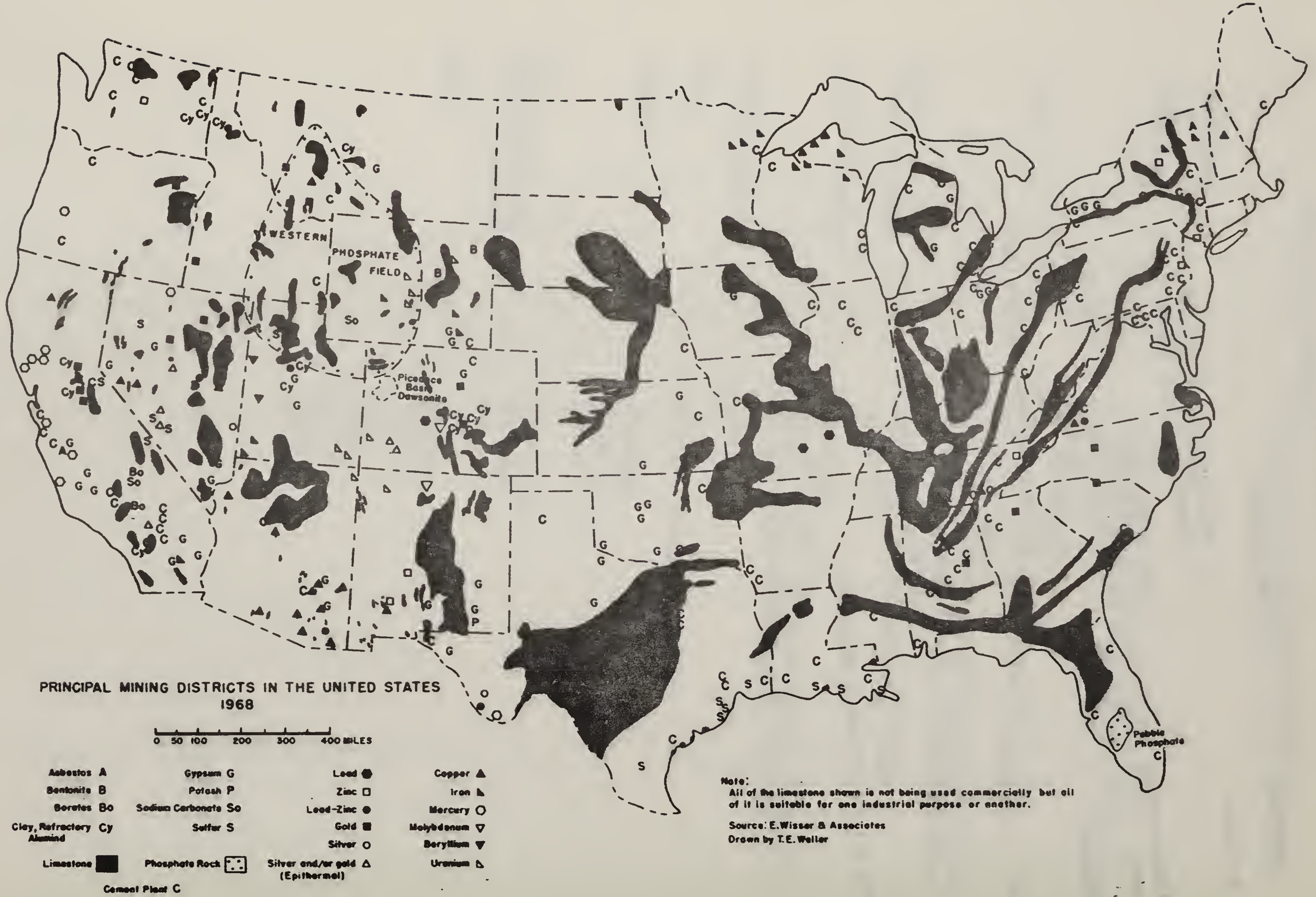
LOCATION OF PRINCIPAL NONMETALLIC MINERAL DEPOSITS IN THE UNITED STATES

Commodity	Location
Phosphate	1. Florida and adjacent states to the north. 2. Western phosphate field–*Montana, Utah, Wyoming,* and *Idaho.* 3. Tennessee.
Potash	1. Texas–*New Mexico* border (Carlsbad area). 2. Moab, Utah. 3. Southern *California* (saline and dry lake deposits, in association with borate and sodium minerals).
Boron (borate minerals)	1. Saline and dry lake deposits in Southern *California.*
Sodium Carbonate	1. *Wyoming.* 2. Southern *California,* saline and dry lake deposits. 3. Oil shale region of *Colorado-Wyoming-Utah.*
Sodium Sulfate	1. Texas
Sulfur	1. Southern Texas and Louisiana.
Asbestos	1. Vermont. 2. *California.* 3. *Arizona.*
Perlite (acoustical and heat insulation material)	1. *New Mexico.* 2. *Colorado.* 3. *Arizona.*
Gypsum	1. *California.* 2. Michigan. 3. Iowa. 4. Texas. 5. *Arizona.* 6. Virginia. 7. New York.

Table 10 (Continued)

Commodity	**Location**
Bentonite	1. *Wyoming*, South Dakota 2. Mississippi, Texas, *Arizona.*
Diatomaceous earth	1. *California.* 2. *Nevada, Oregon, Washington.*
Flourspar	1. Illinois, Kentucky. 2. *Colorado, Montana, Nevada, Utah.*
Talc	1. *California.* 2. North Carolina. 3. Texas. 4. New York.

States in *italics* are public land states.



Note:
All of the limestone shown is not being used commercially but all of it is suitable for one industrial purpose or another.

Source: E. Wisser & Associates
Drawn by T.E. Weller

Fig. 61 - Principal nonfuel mineral producing districts of the United States in 1968. Although most metallic minerals are now produced from deposits west of the Mississippi River, the location of industrial minerals production is more closely related to the nation's population distribution.

E. CHANGES IN MINERAL RESOURCES EXPECTED BY 1985

1. Changes in Mineral Deposit Characteristics

The large, low-grade, disseminated mineral deposit will undoubtedly become more important in the nation's mineral resource picture over the next two decades. This will be true not only for those commodities currently found in such deposits but for others as well.

While the types of host rocks associated with valuable mineral deposits may not change drastically by 1985, it is highly probable that extrusive igneous and sedimentary rocks will be more frequently found to contain deposits of valuable minerals. The nature of those valuable minerals will also change, with silicates becoming more important as ore minerals replacing the current dominance of sulfides, oxides, and carbonates.

Changes in the mineral composition of the ores of lead, zinc, gold, mercury, and potassium before 1985 are not anticipated. The ore minerals presently mined for these elements should continue to be their most abundant economic source. Gold is included in this group because native gold is still the basic source mineral for the yellow metal even in deposits like those at Carlin and Cortez, despite the fact that the host rock is vastly different from previously known deposits.

The projected demand for titanium may encourage greater mining of iron deposits rich in titanium minerals including ilmenite, an iron-titanium oxide. The difficulty of profitably separating iron from titanium in many deposits containing both metals has in the past rendered most of these deposits uneconomic as sources of either.

Advances in the technology and economics of copper leaching and electrowinning with the production of high-purity copper right at the mine have stimulated the development of low-grade deposits of selected secondary copper minerals (copper oxides, copper silicates, and copper carbonates), particularly within the past three years. "Oxide" copper deposits containing malachite, azurite, chrysocolla, and tenorite or melaconite have in the past had to be relatively high-grade and inexpensive to mine because of the high cost of extracting copper from these minerals. Although copper sulfides will probably continue to be the major copper ore minerals, copper oxide and silicate minerals should increase in importance as an economic source of copper by 1985.

The sharp increase in the prices of silver in recent years has promoted exploration for large, low-grade deposits of this metal. Minerals valuable partly or principally for their copper and lead content (e.g., galena, tetrahedrite) have heretofore been major ores of silver. Large low-grade deposits of silver which can be expected to be discovered and developed in the future will contain ore minerals whose chief value is in the silver itself, including cerargyrite (silver chloride), the ruby silver minerals, argentite (silver sulfide), native silver, and possibly some as yet unknown silver minerals.

Beryl has heretofore been the chief ore mineral of beryllium. The large beryllium deposits in volcanic rocks in Utah contain other beryllium minerals, however, which should become the nation's major source of beryllium as these deposits are put into production.

Trona and rock salt deposits should continue to be the major sources of sodium in the United States in 1985. New sources may develop, however, from the sodium minerals, dawsonite and nahcolite, which are associated with the "oil shale" deposits of Colorado, Utah, and Wyoming. Some regions containing suitable rock exposures but lacking large supplies of sand and gravel will (as is now done in the San Francisco Bay area) increase their use of crushed and broken rock for aggregates.

Mineral commodity prices reflect the relationships of supply to demand. If demand increases, thereby raising prices sufficiently, previously unprofitable low-grade deposits of some minerals (now produced largely as by-products or with other ores) may come into production, thus changing the ratio of by-product to primary production for those commodities. The converse is also true. Certain assumptions can be made regarding demand and other causal factors upon which to project trends, but no probability of their correctness can be determined. The number and type of new ore deposits which will be discovered and put into production over the next fifteen years is just about as unpredicatable. Projections must, therefore, be considered subject to change depending upon changes in the factors upon which the projections are based.

2. Changes in the Economic Grade of Mineral Deposits

If recent trends in the technology and economics of gold mining continue, by 1985 gold placer deposits, to be commercially useable, will have to contain at least .01 of an ounce of gold per cubic yard of gravel. Gold ores in place, however, may remain relatively constant in average grade at the current level of about 0.35 of an ounce of gold per ton of ore. Much of the change between now and 1985 will depend, in many respects, upon the success or failure of large-scale open-pit gold mines such as those at Carlin and Cortez, Nevada.

The average grade of silver ore mined in the United States is likely to decline by 1985, probably to an average of about 16 ounces per ton. The average grade of silver deposits mined in 1985, however, could fall below eight ounces per ton and could rise above 20. The pattern of metallic content in silver ores in the past has been erratic, and the pattern in the future may be expected to be equally as variable.

If current trends continue in the demand for and the supply of mercury, the average grade of mercury deposits mined in the United States will probably continue to decline, probably to an average of about six pounds per ton by 1985. Variation could be erratic, however, and could go as high as ten pounds per ton or drop to ore deposits of extremely low grade, i.e., containing less than one pound per ton.

Among the base metals, variation in grade by 1985 may also be highly variable, particularly in lead and zinc deposits. By 1985 the average grade of lead deposits mined in the United States will probably fall to between 2.5 and three percent recoverable lead. It could go much higher, however, exceeding four percent before the middle 1970's, or it could again drop as low as two percent by 1985. The average grade of zinc ores mined in the United States between 1968 and 1985 may be expected to vary just as much as the average grade of lead ores.

By 1985, the average grade of copper ores mined in the United States will probably fall below 0.5 of one percent recoverable copper and could go as low as 0.4 of one percent. The average recoverable iron content of iron ores mined in the country will probably also continue to follow a declining path and could go as low as 10 percent iron by 1985 and will probably be no greater than 20 percent by that year. Such a decline in the average grade of mineable iron ore deposits could have a significant impact upon many deposits throughout the Western United States not now considered economically useable.

Among the lesser metals, the average grade of molybdenum deposits may be expected to decline between 1968 and 1985 and could go well below 0.1 of one percent molybdenum by 1985. Similarly, the average recoverable content of nickel ores mined in the United States will probably continue to decline between 1968 and 1985, and will probably approach 1.3 percent or at least be well below 1.4 percent by that year.

The future of uranium is questionable. The grade of uranium ores has been erratic in the past, and it can be expected to be just as erratic in the future. By 1985 the average recoverable content of uranium ores mined in the United States could go as low as 0.1 of a pound of U_3O_8 per ton of ore and will probably fall well below 0.2 of a pound per ton.

The average grade of most industrial mineral deposits mined in the United States will probably remain relatively unchanged between the late 1960's and 1985. The average grade of phosphate deposits, however, is likely to increase by 1985. The average grade of phosphate rock mined in the United States (if it is at all available) will probably increase above 18 percent P_2O_5 and could go as high as 22 percent. This, of course, assumes that deposits containing such concentrations are available for mining.

3. New Sources of Minerals

Just as the nature and grade of currently utilized types of mineral deposits will change by 1985, so also is it likely that completely new types of sources will be found for some minerals. And some minerals not now considered valuable will become so. Various mineral commodities occur in nature in forms and concentrations which are not now of great economic interest. Potential advances in technology and rising demand, however, may enable these mineral occurrences to be profitably mined in the future. There are numerous examples of such resources.

Certain sedimentary formations contain very low concentrations of some metals which are not of economic interest at this time, but which could be in the not too distant future. Large areas of the Chinle shale on the Colorado Plateau contain small amounts of mercury, and the Chattanooga shale in the Eastern United States contains higher-than-normal concentrations of some metals.

Some coal and lignite deposits are relatively rich in some metals such as uranium, copper, nickel, cobalt, and germanium. Ash from the burning of coal and lignite has been an economic source of uranium and germanium in some cases. Further research could develop economic processes for the extraction of various metals from ash produced at coal-burning power plants or at plants producing coal for chemical purposes. Some petroleum raw materials (e.g., oil shale) might have similar possibilities.

Similarly, many phosphate beds in the United States contain minor amounts of vanadium, uranium, and fluorine which in the past have been extracted as by-products in the production of phosphate fertilizer compounds. Given sufficient demand the phosphate deposits could become significant sources of uranium, flurorine, and other elements, produced as by-products of fertilizer manufacture.

The geothermal brines in the vicinity of the Salton Sea, California, contain high concentrations of silver and other metals. Utilization of these brines as an energy source could lead to the development of profitable extraction processes for their contained metals and other chemical compounds. Elements and compounds occurring in brines and in sea water exist as dissolved ions, rather than as minerals in the technical sense. The chemical or mineral forms of mineral commodities occurring in the other environments mentioned above are presently not well-known in all cases. Some may occur as metal sulfides while other may be contained within the molecular structures of other minerals or organic compounds (e.g., in coal, lignite, or tar). Research on the production of fresh water from sea water by desalinization plants operating on atomic energy has been in progress for several years. Many elements and compounds must be removed in the process of purifying the water. It is conceivable, therefore, that economic processes may be developed to concentrate, from the unwanted residue, certain compounds and elements, including gold.

Considerable investigation has also been made regarding the occurrence and economic potential of large concentrations of manganese nodules on the ocean floors. These nodules contain significant amounts of copper, nickel, cobalt, and other metals. Profitable methods for the mining of these nodules have not as yet been proven. It would not be surprising, however, to see such methods developed within the next fifteen years.

Just as the oceans are known to cover mineral resources, it is a virtual certainty that the basaltic flows of the Columbia River volcanic province in the Northwestern United States form an effective cover concealing many gold deposits, and probably many of silver, lead, and zinc as well. Wherever this great lava field is bounded by older rocks, these areas are literally studded with mining districts which have produced gold, silver, lead, zinc, or copper.

The Columbia Plateau lava flows, mainly of basalt, are very thick in places, but they were laid down over rough terrain. For example, the Blue Mountains in Northeastern Oregon, rich in gold, with some silver and copper deposits, stand up like an island in a sea of basalt. It seems likely that the lava flows never did cover them. It seems also a certainty that throughout the region there must be other mountain ranges which are only slightly submerged, and where metallic mineral deposits might be found by the advanced exploration methods of the future, methods which are being developed even today. Ore deposits within such buried mountains might well lie within the economic depths of mining, either by open pit or large-scale underground methods.

The West contains many areas of surface volcanics much thinner than the Columbia River basalts, and still larger areas of relatively thin surface alluvium. Where mineral deposits carry sufficient sulfides to make them detectible by electrical methods, they might be found in such areas even by presently known exploration techniques.

Increased future production from new and expanded disseminated copper mines should tend to raise the percentage of by-product gold produced in the United States. Offsetting this tendency, however, is the fact that the gold content of the copper ores tends to follow the copper content, which is decreasing and will probably continue to decrease through 1985.

The Carlin, Nevada, gold deposit was brought into production in 1966, and the Cortez, Nevada, gold deposit, which is being developed, should come into full production shortly. Both of these deposits are of the large low-grade, open-pit type and will add substantially to primary domestic gold production, thus offsetting the expected absolute increase in by-product gold. The Carlin mine should still be operating in 1985 and quite possibly the Cortez mine will be as well. Chances seem good for the further discovery of similar deposits, not only in Nevada but elsewhere in the West.

For gold mining, a whole new range of possibilities is being opened up. It is now known that gold deposits in which gold is *not* visible to the human eye do exist. Furthermore, those deposits of this type that have been discovered to date are mineable by relatively inexpensive open-pit methods. In Northern Nevada there are literally hundreds of square miles showing rocks similar to those bearing gold at Carlin and Cortez, all located in the same structural belt that provided the structures that localized the Carlin and Cortez deposits.[132]

Present knowledge indicates that the Homestake gold deposit may become exhausted prior to 1985, thus tending to decrease the supply of primary gold. Exploration for large, low-grade gold deposits is active, however, and it can be expected that new gold mines will be discovered and brought into production before 1985. If the world price of gold continues to remain above 35 dollars an ounce, and particularly if it increases further above the present price, some gold deposits previously shut down may again be utilized, and the Homestake deposit may have its life extended.

Since 1947, the average percentage of by-product gold production has been gradually increasing. Projection of the trend since 1947 indicates that by-product gold will account for about 40 percent of the nation's gold output by 1985. This average percentage will depend, of course, upon the ratio of new gold mines to new disseminated copper mines placed on-stream in the next 15 years. If new large, low-grade, surface gold deposits are discovered and put into production during this period, the proportion of by-product gold could fall to the 30 to 35 percent range.

Gold is not the only metal to be recently found occurring in large, disseminated deposits. As one authority has reported,

> ". . . a study of a number of old silver camps in the Southwest (as well as in Mexico, Peru, and Chile) has indicated that, surrounding high-grade, near-surface veins which were mined out many years ago, there are large tonnages of disseminated, near-surface silver deposits of a grade which, with prices that might be anticipated during the next decade, might permit large-tonnage, low-grade silver mining. As one example of such an occurrence, one company has been exploring the low-grade, near-surface silver deposits in the western part of the old Calico Mining District in Southeastern California. Our studies have reached a stage where we feel that detailed exploration may be able to develop substantial tonnages of near-surface, low-grade silver ores in many old mining districts in the southwest (as well as in Mexico, Peru, and Chile)."[133]

The increase in the price of silver from 90 cents per ounce in 1961 to more than two dollars an ounce has turned previously low-grade waste into ore and stimulated exploration for large, low-grade, disseminated deposits amenable to open-pit mining, as well as renewing interest in known low-grade silver deposits. Disseminated silver deposits have been discovered at Calico in Southeastern California. When these deposits and other similar deposits yet to be discovered are placed in production, they will sharply increase the percentage of silver produced from ore in which it is the primary metal of value. A small open-pit operation producing 10,000 tons per day of ore containing three ounces of silver per ton in 1966 would have raised primary product silver percentage of the nation's silver output from 33 to approximately 54 percent. Such an operation, or operations, are probable within the next five to ten years and should more than offset anticipated increases in by-product production from new or expanded base metal mines.

In late 1967 and early 1968, industry and financial predictions were for the price of silver to climb to three to five dollars an ounce within the next few years, due to increasing demand and the shortage of the metal. More recent market behavior indicates, however, that a significant portion of recent silver demand has been due to speculation. Moreover, production from deposits such as those at Calico would satisfy a large portion of the increased demand and tend to hold prices down.

Electrical manufacturers have recently expanded production of silver-clad copper items, previously made entirely of silver, in an effort to hold down costs. Eastman Kodak has been developing a substitute for silver to use in the manufacture of photographic film, one of the major categories of silver consumption. If and when a substitute comes into active use, the rate of increasing demand for silver would be temporarily reduced until increased use of silver in other products could take up the slack.

The use of silver substitutes could result in sharply lower prices for silver, making low-grade silver mineral deposits unprofitable to mine. This would substantially decrease the amount of primary silver production. The amount of by-product production from lead-zinc ores might also decrease, but that amount derived from disseminated copper ore would probably remain essentially unchanged. The silver in western lead-zinc ores contributes substantially to their total value, but is too low-grade (a few tenths of an ounce, at best) in the nation's copper ores to make any difference in the value of the ore as mined. The net result would be to increase the percentage of by-product silver production.

Projection of the current trend indicates that silver derived from primary silver ore will account for approximately half of total domestic production by 1985. If the Calico and other similar deposits come on-stream, this figure could rise to 75 or 80 percent of total United States production. Conversely, widespread use of a silver substitute in photographic applications could reduce this figure to 30 percent or less.

Nevertheless, active exploration is presently going on, especially in the Basin and Range region of the West, in search of traditional "straight silver" deposits such as those at Tonopah, Nevada. Some success appears likely. Of an even stronger bearing on possible conditions in the silver mining industry in 1985, however, is the current search for large disseminated silver deposits. One such disseminated silver deposit has already been found, the deposit at Calico, California, but is not yet under development. The "Silver Belt" in the Coeur d'Alene district of Northern Idaho will probably still be producing in 1985.

Most present copper producing areas will probably still be producing in 1985, but some of the older and some of the smaller porphyry coppers (e.g., Bisbee) may be approaching exhaustion by that time. On the other hand, new deposits will undoubtedly be found. In Southern Arizona, major faulting has taken place since formation of the disseminated copper deposits some 70 million years ago, and such faulting has hidden many deposits. In the late 1950's, a small, independent prospector started a drilling program west of the known San Manuel ore body. It was theorized that part of the original mineral deposit had been moved down by movement along a fault. The theory was confirmed by discovery of the great Kalamazoo ore body, since acquired by the owner of San Manuel.[134] By this acquisition, that company may have doubled its known ore reserves. Careful geologic study and subsequent exploration drilling may work the same miracle for other porphyry copper deposits in this highly faulted region.

Chances also strongly favor the finding of other deposits similar to the Pima in Arizona. At Pima, the higher ground adjacent to the present alluvium-covered productive area was long the scene of sporadic small-scale mining for silver, copper, lead, and zinc. Similar mineralized areas which abound throughout the West may offer promise for the porphyry copper type of deposit. A possible example is the Patagonia district, six to 15 miles northeast of Nogales, Arizona. There, large masses of granitic rocks intrude limestone, quartzite, and shale. In the past the district has produced silver, lead, and copper, but only in small amounts.[135]

The Helvetia, Arizona, district, 30 miles north of the Patagonia district and 20 miles east of the Pima district, also presents possibilities. There granitic rocks intrude limestone, and the geologic structure is highly complex, for the sediments are strongly folded and faulted. Complex structures often conceal valuable mineral deposits which are discovered only after the complex structure is thoroughly understood, as was the case with the Kalamazoo discovery. The Helvetia district has already produced some copper, silver, and lead.[136]

In the Safford district, between Safford and Morenci in Eastern Arizona, deep drilling since 1947 has disclosed the presence of several major, low-grade copper mineral deposits in lava flows known as "older volcanics." The tops of these deposits lie as much as 1,000 feet beneath the surface. The depth, low copper content, and metallurgical problems make these deposits non-commercial at present, but they may well be in production by 1985. While Safford provides the only domestic example presently known of major copper deposits entirely in volcanics, there are such deposits in Chile.[137] There are also many other surface exposures in Arizona of the "older volcanics" that are known to carry the same copper minerals found at Safford.

Arizona produces more than half of the nation's primary copper production and almost a fifth of free world production.[138] Furthermore, new open-pit copper mines are being put into production in the state and will be on-stream within the next few years. Anaconda[139] expects to have its Twin Buttes open pit south of Tucson on-stream by the end of 1969 at a rate of at least 30,000 tons of ore per day. The company also has a deposit of unspecified size near Helvetia, southeast of Tucson. The Duval Corporation is placing its Sierrita property, adjacent to its Esperanza mine south of Tucson, into production. Magma Copper has announced plans to increase production at its San Manuel operation from 40,000 to 60,000 tons of ore per day and to exploit the Kalamazoo ore body which adjoins it on the west.[140] The El Paso Natural Gas Company is working on its Lakeshore property south of Casa Grande, Arizona, and as mentioned both Phelps Dodge and Kennecott have mineral deposits near Safford, Arizona, which may come into production before 1985. Cyprus Mines Corporation also has a deposit of undisclosed magnitude at Johnson Camp, Arizona, which has been under investigation in recent years.

Elsewhere in the West, Phelps Dodge is preparing its Tyrone, New Mexico, deposit for open-pit production. Kennecott has a copper deposit at Glacier Peak, Washington, which could also be placed in production within the next five to ten years. United States Smelting and Refining is developing a small copper deposit in Southern New Mexico near Kennecott's Santa Rita operation.

Exploration for copper mineral deposits in Arizona has been intense for the past ten years, and is expected to continue at a high rate for at least the next five years. At the same time, however, exploration is increasing in Nevada and the Pacific Northwest. Some of the major copper deposits in Arizona may become exhausted prior to 1985, depending upon economic conditions and whether additional copper ore reserves are developed in the interim to replace ore mined out at these properties.

The lead time from inception of an exploration program to discovery of, and production from, a porphyry copper ore body has ranged from four to ten years or more. Even though some of the older copper deposits in Arizona may cease to provide further production, new deposits coming into production combined with known deposits which may be put on-stream in the next ten years will probably ensure Arizona's position as a leading copper producer through 1985. Because of the lead time in exploration and development, it would require an extraordinary number of discoveries in Nevada and the Pacific Northwest within the next few years to cause a geographic shift in production of any great magnitude to these states prior to 1985.

Within the past few years, copper production from the Lake Superior region has increased essentially because of the development of the White Pine deposit. Should it increase further, and should new mines be developed in Nevada and the Pacific Northwest, Arizona's share of domestic copper production could be whittled down to some extent.

Changes in copper production from large porphyry deposits will also affect the nation's molybdenum supply since such deposits are likely to remain a major source of by-product molybdenum. Near-term increases in primary molybdenum production, however, may hold down or reduce the percentage of total production now accounted for by by-product molybdenum. Over the longer term, existing molybdenum mines will probably increase production rates, compensating for increases in by-product molybdenum from copper mines. The tug of war between molybdenum and copper mine production of molybdenum will fluctuate according to varying rates of expansion in both types of metal mining.

By-product molybdenum will probably account for between 35 and 45 percent of total domestic production by 1985. The percentage of by-product molybdenum will probably increase at a gradual rate, reaching an average figure of about 40 percent by 1985. The accuracy of this projection, however, is quite tenuous, as it depends heavily upon the extent to which new mines of *both* copper and molybdenum are put into production.

Areas of disseminated molybdenum sulfide mineralization in Western Arizona, Nevada, and California are presently known and may some day become the sites of producing mines. By-product molybdenum production from disseminated copper deposits will increase as new mines are opened and existing ones are expanded. However, the Urad and Henderson deposits near Climax are being developed and will add to the Climax area's output. Barring unforeseen developments it seems likely that Colorado will maintain its position as the nation's largest molybdenum-producing state through 1985.

Although Colorado was also the major source of uranium, it was subsequently supplanted by New Mexico. Since 1964, anticipated increases in the demand for uranium have resulted in major exploration efforts to find new ore deposits. A considerable portion, if not most, of these exploration efforts have been concentrated in Wyoming. This exploration, if successful, may forecast a shift in the concentration of domestic uranium production to Wyoming by 1985.

A number of changes in the supply of some of the minor metals can also be expected by 1985. The demand for antimony is increasing at a rate of about two percent a year. Foreign sources of supply, however, are expected to continue to dominate the market. Unless the price of antimony is substantially increased either through loss of foreign supplies or the development of a much greater demand than is now foreseen, the percentage of antimony produced domestically as a primary ore constituent is expected to remain in the five to ten percent range through 1985. Similarly, unless the supply-demand picture is changed by the loss of foreign supplies, substantially increased demand, and/or the discovery of large high-grade reserves in the United States, cobalt will continue to be a by-product of other metal production through 1985. Likewise, unless new uses are developed which would increase demand sufficiently to make it more valuable than the other metals with which it is normally associated, bismuth is expected to remain solely a by-product of other ores through 1985.

In general, the old centers of domestic mercury production in California and Nevada have remained dominant since 1946, although several new deposits have been found and new ore discoveries made at old mines. Stimulated by the present high price of mercury, however, attention is turning to the possibility of mining large, low-grade deposits amenable to open-pit mining. A possibility for this might be offered by the so-called "opalite" deposits in Nevada. These are relatively flat, lie close to the surface, and could be suitable for open-pit mining. Their development before 1985 is a distinct possibility.

No production of nickel existed in the United States until the Hanna Mining Company started production of ferro-nickel at its plant near Riddle, Oregon, in 1954. The deposit has an estimated life of nearly 60 years at the current rate of production and will presumably be producing in 1985. Meanwhile, other nickel deposits may be found in laterites similar to those at Riddle, either in Oregon or Northern California. Exploration for nickel is also being conducted in Northern Minnesota, but no significant deposits have been developed there as yet.

Aside from sporadic minor output in Arizona, there was no major production of asbestos in the United States until the Jefferson Lake, California, deposit came into production in 1962. The deposit lies in the Sierra Nevada Foothills east of Stockton, California. In the same year, production started of very short-fiber asbestos in the Coalinga area, in the Coast Ranges of California, about 70 miles southwest of Fresno. These deposits contain hundreds of millions of tons of asbestos-bearing rock. Under existing geologic knowledge and economic conditions, it seems unlikely that any new centers of production will appear for many years after 1985.

Phosphate reserves in Florida in 1965 were estimated at two billion long tons, with 23 billion potential tons, and in Idaho, Montana, Utah, and Wyoming at three billion tons, with 20 billion potential tons. There is one serious technological problem connected with western phosphate rock, however. The sedimentary beds in which it occurs are highly folded and faulted, unlike the eastern deposits of Florida and Tennessee, which lie flat. In the foreseeable future, in order to tap the enormous western reserves, underground mining will probably have to be used. With the present stage of mining technology, only the high-grade deposits can be mined underground, where mining costs are far higher than with surface mining.[141]

F. SUMMARY

There have been many changes in the known nonfuel mineral resources of the United States since the beginning of the westward movement of population in the last century. The discovery of gold placers was made in California in 1848. The search for similar deposits was carried on throughout the West in subsequent years with the most productive being found in Montana in the 1860's. Indirectly, the search for gold placers led to the discovery of many silver and base metal deposits, such as the Comstock Lode in Nevada, Leadville in Colorado, Bingham in Utah, and the Arizona copper districts.

Over most of the Western part of the nation, interest in silver had barely started by 1860, but in the Southwest, conditions were different. The Gadsden Purchase of 1854 moved the southern border of Arizona to the south, adding a sizable strip of what had been Mexican territory. This area is the northwestern extension of the great silver province of Mexico, in which silver mining had been going on for hundreds of years. Silver mining in Southern Arizona was a tradition, so that it is not surprising that several deposits in the area were producing silver in 1860.

In 1860 the Western United States was at the very threshold of one of the most tremendous expansions of the mining industry in history. Although gold, silver, and mercury were already being produced, the only lead deposit in production in the Western United States in 1860 was the Mowry lead-silver mine in Arizona.

The high-grade copper deposits of the West were all discovered in 1877 or earlier, most of them as a result of the search for precious metals. But unlike the gold, silver, and lead-silver deposits, where mining usually began shortly after discovery, the utilization of these deposits of copper, which as a base metal requires more industrial development (especially transportation) than do the precious metals, there was commonly a considerable lag between discovery and production.

From 1860 to 1882, the Lake Superior region of Northern Michigan accounted for more than two-thirds of total United States copper production. As mines in the West were developed, the Lake Superior region's share of production fell. Beginning about 1880, Arizona and Montana became important copper producers. By 1900 Lake Superior production had dropped to less than a fourth of the total, while Butte, Montana, had become the largest domestic producer. Michigan, Arizona, and Montana combined accounted for almost 90 percent of total copper production. The shift in production toward the Western States continued, however, and by 1915 the Lake Superior region's share had fallen to one-sixth and districts in Arizona, Montana, Utah, Nevada, and New Mexico accounted for two-thirds of all domestic copper production. Arizona has been the leading copper producer since 1910, and has continued to maintain its lead. Several new open-pit copper mines are being put into production and will be on-stream within the next five years.

For both economic and metallurgical reasons, western zinc production came relatively late. All of the lead carbonate and silver deposits known initially turned to lead and zinc sulfide deposits at depth. Exploitation of such zinc mineralization began at Park City, Utah, in 1905, at Bingham, Utah, in 1909, and at Tintic, Utah, in 1912.

Iron, even more than copper and zinc, had to await the growth of industrial markets in the West. Although production of iron ore began in the Hartville district of Wyoming in 1902, no important production took place elsewhere in the West until the 1920's when a steel plant was built at Provo, Utah. In Nevada, considerable iron ore was mined during World War II, but demand lapsed afterward and production was not resumed until 1951. In California, little iron ore was mined until 1942, when Kaiser Steel started its operations in San Bernardino County.

Production centers of mercury have not shifted appreciably since discovery of the New Almaden Mine in California in 1824. New districts have been discovered in this century in Nevada, Oregon, and Idaho, but California remains the chief center of production.

There was no notable production of nickel in the United States before the Riddle, Oregon, deposit came to production in 1954. Since then, that deposit has been virtually the sole domestic source of nickel.

To provide raw materials for the Manhattan Project of World War II, major United States uranium production came from the Uravan district of Southwestern Colorado. In the early 1950's, major deposits were discovered near Grants, New Mexico, and principal production shifted to there. Since 1964, important discoveries in Wyoming may forecast a shift in major production to there by 1985. The Colorado Plateau area has remained so far, however, the nation's principal source of uranium.

The area of phosphate rock deposits, in Idaho, Montana, Utah, and Wyoming, is relatively well defined. Production began there in 1906 and has continued steadily. None but local shifts in production centers have taken place or are anticipated.

> "The geologic make-up and environment of mineral deposits are basic factors that determine what they may yield in the course of time, but other factors, such as the tides of human migration and the provision of transportation facilities, tend to determine the time of their development, and many other factors, such as prevailing prices and the improvements in the arts of mining and metallurgy, determine the parts that are removed from time to time."[142]

This is true not only for phosphates and the base metals but for every other industrial mineral as well. All of these factors have governed the development of mineral resources in the Western United States.

FOOTNOTES

52/ T.A. Rickard, *A History of American Mining*, New York: McGraw-Hill Book Company (1932), p. 20.

53/ *Ibid.*, p. 33.

54/ *Ibid.*, p. 33.

55/ W. Lindgren, *Mineral Deposits*, New York: McGraw-Hill Book Company (1933), p. 930.

56/ A. H. Koschmann and M. H. Bergendahl, "How About Gold?", *Mining World* (January 1961), pp. 26-28.

57/ T. A. Rickard, *op. cit.*, p. 185.

58/ *Ibid.*, pp. 115-117.

59/ W. H. Emmons, *Enrichment of Ore Deposits*, U.S. Geological Survey Bulletin 625 (1917), pp. 55-56.

60/ T. A. Rickard, *op. cit.*, p. 125.

61/ *Ibid.*, p. 345.

62/ *Ibid.*, p. 188.

63/ *Ibid.*, pp. 93-94.

64/ W. H. Emmons, *op. cit.*, p. 61.

65/ D. F. Hewett, *Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada*, U.S. Geological Survey Professional Paper (1931), p. 69.

66/ W. R. Ingalls, "Chronology of Lead-Mining in the United States," *A.I.M.E. Transcript*, Volume 38 (1908), p. 149.

67/ J. H. Curtis, *Silver-Lead Deposits of Eureka, Nevada*, U.S. Geological Survey Monograph 7 (1884), p. 3.

68/ T.B. Nolan, *The Eureka Mining District*, U.S. Geological Survey Professional Paper 406 (1962), pp. 58-59.

69/ *Ibid.*, p. 60.

70/ Wisser, op. cit. p. 8.

71/ *Ibid.*, p. 9.

72/ *Ibid.*, p. 9.

73/ T. A. Rickard, *op. cit.*, p. 125.

74/ *Ibid.*, p. 133.

75/ Reference on history: *Ibid.,* p. 121; reference on production: W. Cross and E. S. Larsen, *Brief Review of the San Juan Region of Southwestern Colorado,* U.S. Geological Survey Bulletin 843 (1928), p. 116.

76/ T. A. Rickard, *op. cit.,* p. 214.

77/ *Ibid.,* p. 144.

78/ C. H. Dunning, *Rocks to Riches,* Phoenix: Southwest Publishing Co. (1959), p. 86.

79/ J. V. Beall, "Southwest Copper - A Position Survey," *Mining Engineer* (July 1965), p. 164.

80/ Reference on Tonopah: J. E. Spurr, *Geology of the Tonopah Mining District, Nevada,* U. S. Geological Survey Professional Paper 42 (1905), p. 25.

81/ *Mineral Resources of the United States,* U.S. Geological Survey (1900), p. 148.

82/ *Mineral Resources of the United States,* Part 1: Metals, U.S. Geological Survey (1915), p. 165.

83/ *Mineral Resources of the United States* (1900), *op. cit.,* p. 142.

84/ *Mineral Resources of the United States,* Part 1: Metals, U.S. Geological Survey (1915), p. 667.

85/ L. P. Larsen, "The Mineral Industry of Arizona," *Minerals Yearbook* (1963), p. 4.

86/ R. T. Moolick and J. J. Durek, *The Morenci District, Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966), pp. 221-231.

87/ T. A. Rickard, *op. cit.,* pp. 347-353.

88/ F. L. Ransome, *Geology of the Globe Copper District, Arizona,* U.S. Geological Survey Professional Paper (1903), pp. 134, 141, and 144.

89/ D. C. Bryant and H. E. Metz, *Geology and Ore Deposits of the Warren Mining District, Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966), pp. 189-203.

90/ C. H. Dunning, *op, cit.,* pp. 76-79, 113-115, and 149.

91/ A. M. Bateman, *op. cit.,* pp. 500-501.

92/ T. A. Rickard, *op. cit.,* pp. 376-377.

93/ W. C. Browning and F. W. Snow, "Geology and Operations of the Magma Mine," *Engineering Mining Journal* (January 31, 1925), p. 197.

94/ C. H. Dunning, *op. cit.,* pp. 181-182.

95/ W. C. Browning and F. W. Snow, *op. cit.,* p. 198.

96/ T. A. Rickard, *op. cit.,* pp. 192-196.

97/ H. L. Bauer et al., *Porphyry Copper Deposits in the Robinson Mining District, Nevada, Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona (1966), pp. 233-244.

98/ C. H. Dunning, *op. cit.,* pp. 184 and 200.

99/ A. W. Rose and W. W. Baltosser, *The Porphyry Copper Deposit at Santa Rita, New Mexico, Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966) p. 205.

100/ D. W. Dixon, *Geology of the New Cornelia Mine, Ajo, Arizona, Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966), p. 123.

101/ A. B. Parsons, "The Porphyry Coppers in 1956."

102/ C. H. Dunning, *op. cit.,* pp. 235-239.

103/ A. C. Spencer and S. Page, *Geology of the Santa Rita Mining Area, New Mexico,* U.S. Geological Survey Bulletin 859 (1935), p. 66.

104/ W. Lindgren, L. C. Graton, and C. H. Gordon, *Ore Deposits of the Tintic Mining District, Utah,* U.S. Geological Survey Professional Paper 107 (1910), pp. 23 and 210.

105/ B. S. Butler and G. F. Loughlin, *Ore Deposits of Utah,* U.S. Geological Survey Professional Paper 111 (1920), p. 506.

106/ Reference on Park City: *Ibid.,* p. 292; reference on Goodsprings: D. F. Hewett, *op. cit.,* p. 72.

107/ B. S. Butler and G. F. Loughlin, *op. cit.,* p. 346.

108/ *Ibid.,* p. 408.

109/ *Mineral Resources of the United States* (1915), *op. cit.,* pp. 807-808.

110/ *Mineral and Water Resources of Nevada,* Nevada Bureau of Mines, Bulletin Number 65 (1964), p. 106.

111/ *Mineral and Water Resources of Wyoming,* 86th Congress, 2nd Session, Senate Document No.76 (1960), p. 6.

112/ *Mineral and Water Resources of Utah,* 88th Congress, 2nd Session, Committee Print (1964), p. 90.

113/ *Industrial Minerals and Rocks,* American Institute of Mining, Metallurgy, and Petroleum Engineers (1960), p. 658.

114/ *Mineral Facts and Problems,* Washington: U.S. Bureau of Mines, U.S. Department of the Interior (1965), p. 699.

115/ *Minerals Yearbook,* Washington: U.S. Bureau of Mines, U.S. Department of the Interior (1946), pp. 993, 995, and 997.

116/ R. M. Hardy, "A Status of Silver Production," *Mining Congress Journal* (January 1965), pp. 75-83.

117/ *Minerals Yearbook, 1967,* Washington D.C.: U.S. Department of the Interior (1968).

118/ H. M. Hardy, *op. cit.*, p. 64.

119/ *Mineral and Water Resources of Nevada, op. cit.*, pp. 85-86.

120/ K. Richards and J. Courtright, *Structure and Mineralization at Silver Bell, Arizona, Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona (1966), p. 157.

121/ W.T. Smith, "The Lavender Pit," *Mining Engineer* (May 1956), p. 509.

122/ C.H. Dunning, *op. cit.*, p. 258.

123/ *Ibid.*, pp. 264-266.

124/ J.V. Beall, "Southwest Copper - A Position Survey," *Mining Engineer* (July 1965), p. 91.

125/ *Ibid.*, p. 80.

126/ *Ibid.*, p. 92.

127/ *Minerals Yearbook* (1946), *op. cit.*, p. 943.

128/ W.E. Ver Planch, *Boron in Mineral Commodities in California,* San Francisco: Division of Mines, Department of Natural Resources, Bulletin 176 (1957), p. 90.

129/ *Commodity Data Summaries,* Washington: U.S. Bureau of Mines, U.S. Department of the Interior (January 1967), p. 111.

130/ E.D. Wilson and G.H. Roseveare, *Arizona Nonmetallics,* Arizona Bureau of Mines, University of Arizona Bulletin, Vol. 20, No. 2 (1949).

131/ T.Eyde, presentation to the Arizona Geological Society (November 1968).

132/ J.H. Stewart and E.H. McKee, *Favorable Areas for Prospecting Adjacent to the Roberts Mountains Thrust in Southern Lander County, Nevada,* U.S. Geological Survey Circular 563 (1968).

133/ R.M. Dreyer, "Silver Economics and Silver Exploration in the Southwestern United States," *A.I.M.E.* Preprint 6711 (Annual Meeting 1967), p. 3.

134/ P. Lowell, "Discovery and Exploration of Kalamazoo Ore Body," *A.I.M.E.* Preprint 68-I-3 (Annual Meeting 1968).

135/ F.C. Schrader, *Mineral Deposits of the Santa Rita and Patagonia Mountains, Arizona,* U.S. Geological Survey Bulletin 582 (1915), pp. 292-348.

136/ *Ibid.*, pp. 91-141.

137/ Lindgren, *op. cit.* pp. 560-600.

138/ L. P. Larsen, *op. cit.*, p. 4.

139/ *Engineering and Mining Journal*, February 1969 pp. 83-88.

140/ *Ibid.*, p. 86.

141/ *Mineral Facts and Problems* (1965), op. cit., p. 709.

142/ D.F. Hewett, *op. cit.*, p. 69.

143/ McKinstry, *op. cit.*, p. 470.

144/ *Ibid.*, pp. 471-472.

145/ *Ibid.*, p. 472.

146/ *Ibid.*, p. 470.

147/ D.H. McLaughlin, "Biological Factors in the Evaluation of Mines," *Economic Biology*, Vol. 34 (1939), pp. 589-621.

148/ W. Lindgren, "Geographical Features of Gold Production of North America," *A.I.M.E. Transactions*, Vol. 33, pp. 790-845.

149/ E. Seuss, *Die Zukunft des Goldes*, Vienna (1877),

150/ A. Del Mar, *A History of the Precious Metals* (1880).

151/ J.N. Faick, "Geology and Technology of Some Natural Pozzalans in North Central California," *Economic Geology*, Vol. 58 (1963), pp. 702-719.

152/ *Ibid.*, p. 702.

153/ *Ibid.*, p. 700.

154/ *Commodity Data Summaries* (1967), p. 72.

155/ *Paley Report*, p. 31.

156/ *Ibid.*, p. 34.

157/ *Ibid.*, p. 34.

158/ Landsberg et. al *Resources in America's Future* Baltimore: Johns Hopkins Press 1965.

159/ *Ibid.*, p. 44.

160/ *Ibid.*, p. 914.

161/ *Commodity Data Summaries*, Washington: Bureau of Mines, U.S. Department of the Interior (January 1968), p. 72.

162/ *Ibid.*, p. 93.

163/ *Paley Report, op cit.*, p. 94.

164/ *Commodity Data Summaries, op. cit.*, p. 155.

165/ H.J. Winters, *Concentration Ratios and Ease of Entry into Metals Markets*, Tucson: University of Arizona (1968).

166/ *Paley Report, op. cit.*, pp. 91-92.

167/ *Ibid.*, pp. 91-92.

168/ *Public Land Statistics*, Bureau of Land Management, U.S. Department of the Interior (1967), p. 85.

169/ *Ibid.*, p. 92.

170/ *Ibid.*, p. 93.

CHAPTER 5

THE PROBLEMS OF MINERAL RESERVE ESTIMATION

Have estimates been made of the mineral reserves of the United States since 1947? Have these estimates been substantiated by subsequent production figures?

A. CONCEPTS OF MINERAL RESERVES

1. Concepts of Mineral Deposits

As a result of special (and often unique) combinations of geological environments and geological processes, certain localized portions of the earth's crust have been enriched in one way or another in certain mineral components. When such a localized zone of enrichment contains minerals which can be treated to extract a valuable product, and if that zone of enrichment is of such a shape, size, position, and continuity of composition to permit the removal of the enriched rock from the earth in appropriate amounts for such treatment at a cost of removal and treatment that will be less than the saleable value of the product, then that zone is said to be an *orebody* or *valuable mineral deposit.*

Every such zone of enrichment will have boundaries beyond which the particular mineral or minerals involved do not exist in quantities sufficient to make extraction economically feasible. Some of these boundaries will be sharp and distinct while others will be broad and vague. None will be permanent. The size of any given ore deposit at any one time is governed by the position of its boundaries. The value of the ore deposit will be determined by its mineral content, the market value of the product to be derived from it, and the costs required to remove the mineral from the earth and prepare and sell that saleable product.

If an idealized ore deposit or ore district were to be examined, it would be found that a plot of value vs. tonnage would in most instances be represented by an exponential curve (see Figure 62) and generally contain very limited tonnage with high values and increasing tonnages with lower values until an almost infinite tonnage is present as average crustal concentrations are approached. Value distribution within such a mineralized body would probably vary as well, and might be confined, locally enriched, or dispersed. Thus, the tonnage/value curve might be flat, steep, or irregular.

Ore deposits, from an operational point of view, may be classified into three categories. The *bonanza* or *high-grade, selectively mined deposits* are relatively small with a high unit value and generally yield a wide margin of operating profit. Their utilization generally involves a low capital investment and small ore reserves. They have often survived mismanagement and high overhead because of the wide profit margin produced. These bonanza deposits formed the basis for early mining, but are becoming scarce and of little consequence in today's total minerals picture, except in a few selected instances such as in the early years of the first uranium rush.

Selectively mined, moderate-grade deposits are usually moderately-sized ore deposits that must be selectively mined to maintain a profitable grade. As a result they require high labor input. These deposits are gradually disappearing from the list of producers because of rapidly rising labor unit costs relative to increases in mineral prices.

Bulk-low-grade deposits are large deposits of such a size and shape that they lend themselves to low-cost, bulk mining methods and ready recovery of metal values. They are operated on a low profit margin with a high capital investment, but yield a high production rate for each employee and normally have large, established ore reserves. These deposits are very sensitive to cost or value changes, recovery, mismanagement, and taxation.

Dependent upon the shape and attitude of the deposit, the distribution of mineral values

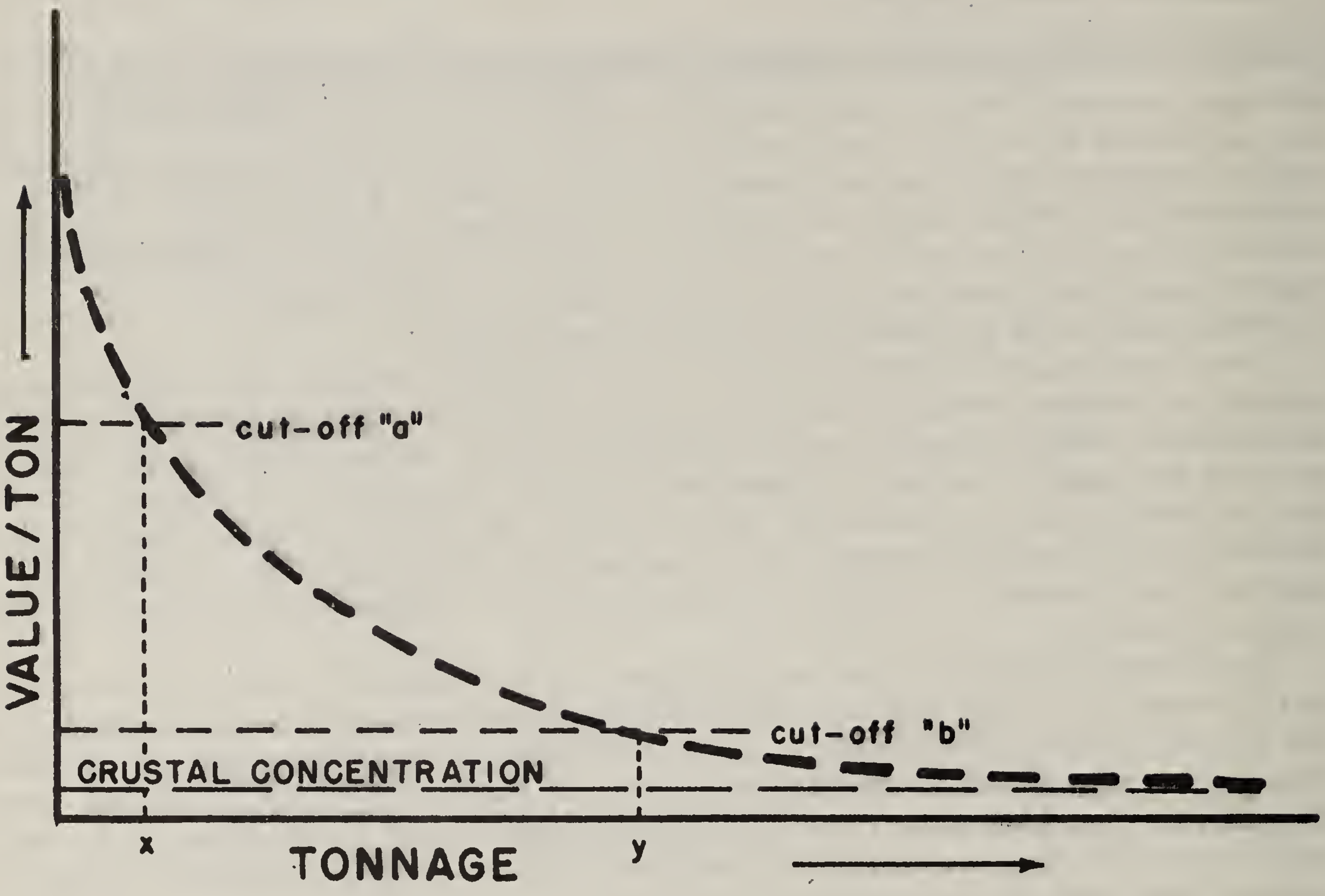


Fig. 62 - An idealized representation of the relationship between total reserve tonnage and valuable content per ton of rock in a mineral deposit. A cutoff grade at "a" would give "x" tons of ore in reserve, while a lower cutoff at "b" would increase the tonnage of reserves to "y".

within the deposit, and the technical recoverability of mineral values, an ore deposit may move from one category into another with changing economic and technological conditions. In bonanza-type deposits, it is common for a sharp boundary to exist between ore and waste. Ore is high-grade and wallrock immediately adjacent to it contains essentially no values. A variety of situations are illustrated in Figures 63, 64, and 65. Veins and ore pockets in the Tombstone, Arizona, area serve as an excellent example of the bonanza-type orebody. Silver values in high-grade shoots at Tombstone range from 20 to 100 ounces per ton, while in the immediately adjacent rock the silver values are of the order of 0.1 ounces per ton. Gold values likewise commonly cease abruptly as do (sometimes) copper, lead, zinc, and mercury.

In the early development of the prophyry copper deposits, only the blanket of enriched ore covering the top of the deposit could be profitably mined. Values in the enriched blanket ran from one to 1.5 percent copper. It was not until economic and technological conditions allowed cut-off limits to drop below 0.7 percent copper that these deposits underwent tremendous expansion as ore boundaries extended into the unenriched material. Likewise, as mineable grade was further reduced, very large deposits that had not undergone enrichment were then able to be developed. Among such are the Sierrita, San Manuel, and the Kalamazoo deposits in Arizona and the Grandisle and Granduc deposits in British Columbia, Canada. In some instances enrichment has resulted in bonanza-type deposits, producing high-grade concentrations of silver (e.g., the Mowry Mine, Arizona, and Lake Valley, New Mexico) and copper (e.g., early production at Butte, Montana, and the United Verde Extension, Arizona). In some instances the underlying unenriched material is well below present economic requirements for ore. Nickel, silver, and copper are the metals that most commonly show this tendency for enrichment, though sometimes gold deposits will also be enriched.

The dispersed distribution of mineral values is characteristic of the bulk-low-grade deposits where ore boundaries are determined only through careful analysis of contained values, and whose shape and size can be considerably modified by minor fluctuations in the cut-off value applied in determining what is and is not ore.

The situations assumed in Figures 66, 67, 68, and 69 are very simple. Figure 70 represents a single ore body with a high-grade center grading uniformly outward into lower value material. In such a situation, changing costs or market prices would shrink or expand the size of the orebody without appreciably changing the technique that might be involved in the mining. Within certain limits, an open-pit, caving operation or room-and-pillar method might be adapted to the changing economic, technologic, and political situations. Unfortunately, these are idealized situations, and few ore bodies with dispersed values are this simple. Deposits that are more representative are shown in Figures 71 and 72. These might be represented by the same value/tonnage distribution curve as the preceding deposits in Figures 66 to 70, but the value distribution lacks continuity. Such deposits require selective mining until the cut-off value can be reduced to some critical level such that the entire orebody or major portions of the mineral deposit can be mined in bulk, thus gaining the advantages of low-cost mining related to the use of large materials handling and processing equipment.

Looking at the situation from a different point of view, a bulk, low-grade mineral deposit faced with rising costs and taxes, or declining metal prices, might require material of such a high grade that bulk methods could no longer be used. Selective, high-cost mining methods would be required and reserves would shrink to small bonanza pockets or veins. Ore reserves might thus completely disappear or at best be drastically reduced.

2. Types of Ore Reserves

There are many terms that have been applied to ore reserves. Basically all of them reflect both current and anticipated geologic and economic conditions. Each type of terminology is useful in individual cases, according to the information available and the particular reserve problem.

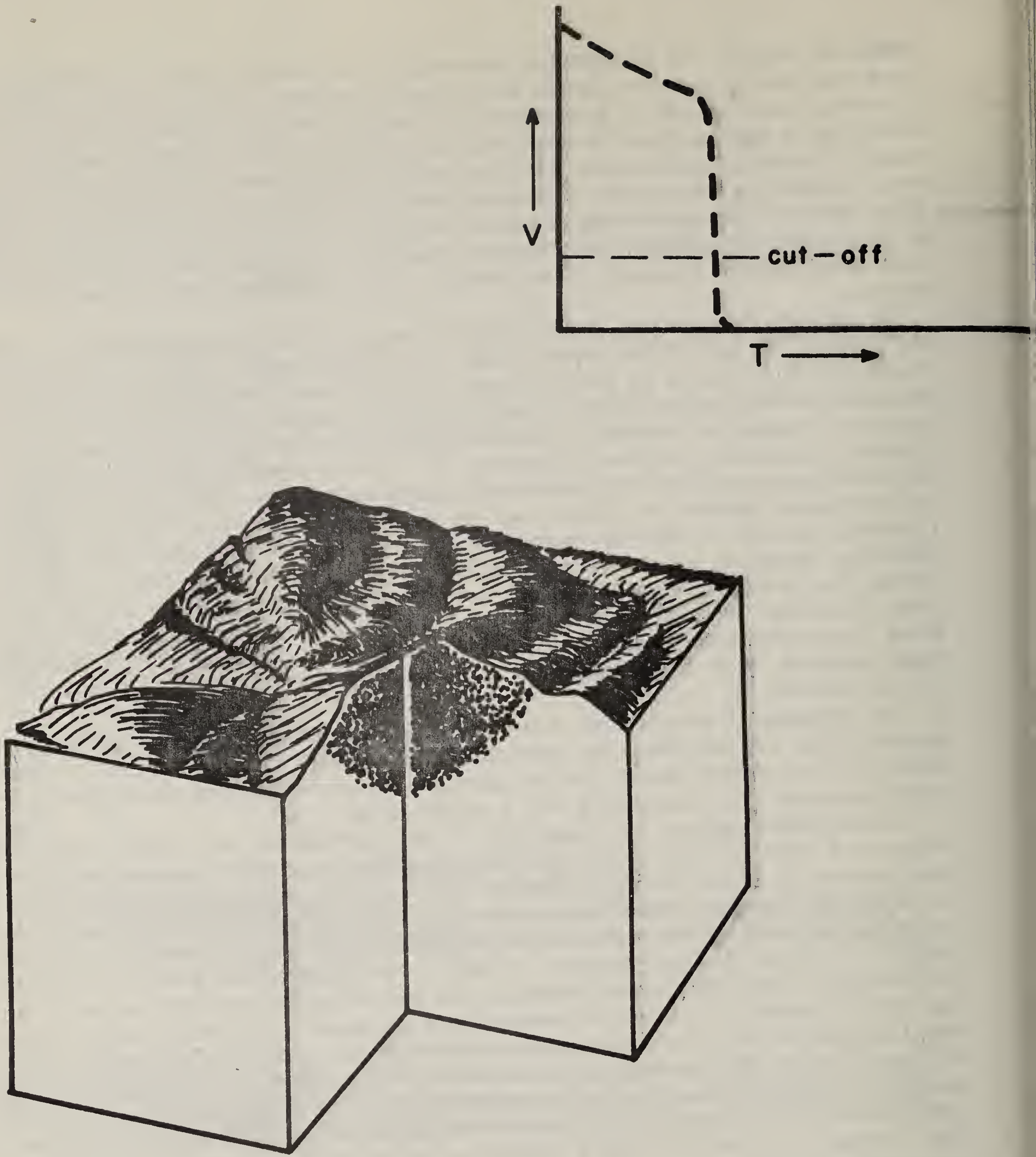


Fig. 63 - An idealized representation of a relatively small, high-grade, "bonanza" type mineral deposit with combined values amenable to selective mining methods. As shown by the graph, cutoff or economic grade can be varied within a relatively wide range without affecting total reserves.

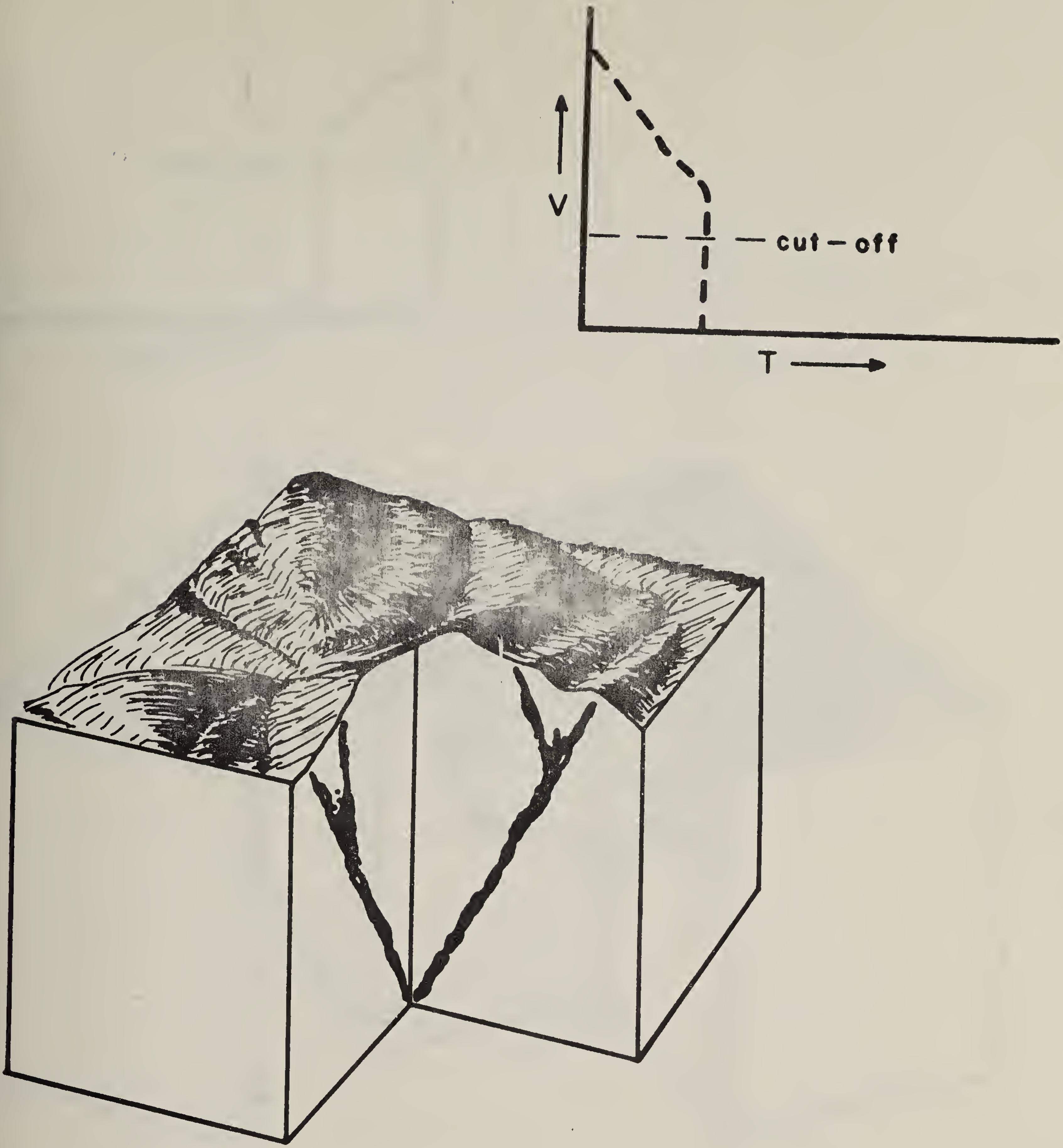
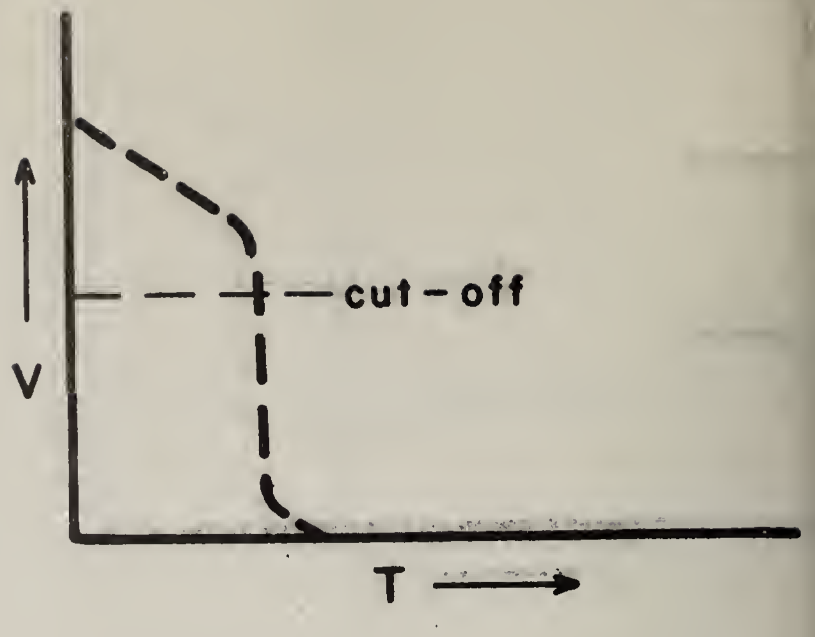


Fig. 64 - An idealized representation of a vein deposit with confined values. Many of the early gold and silver "lode" deposits were of this type. Variation of the cutoff grade, except to the extremes, has relatively little effect on total reserve tonnage.



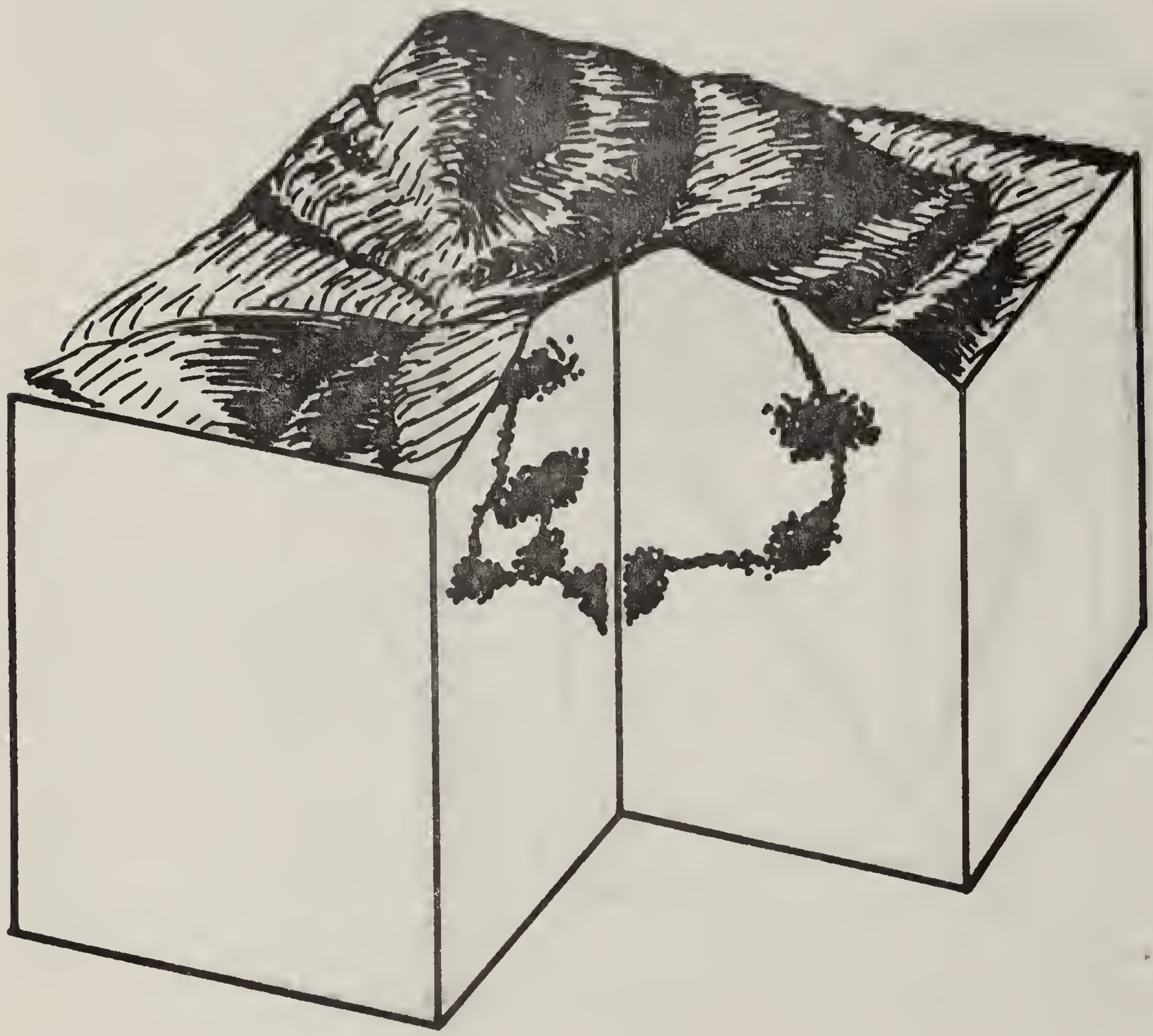


Fig. 65 - An idealized representation of an irregular, pockety deposit with confined values. The discontinuous nature of ore mineral occurrence results in higher mining costs and thus a higher cutoff grade and lower reserve tonnage. Any additional costs imposed on such a deposit could make it a marginal resource.

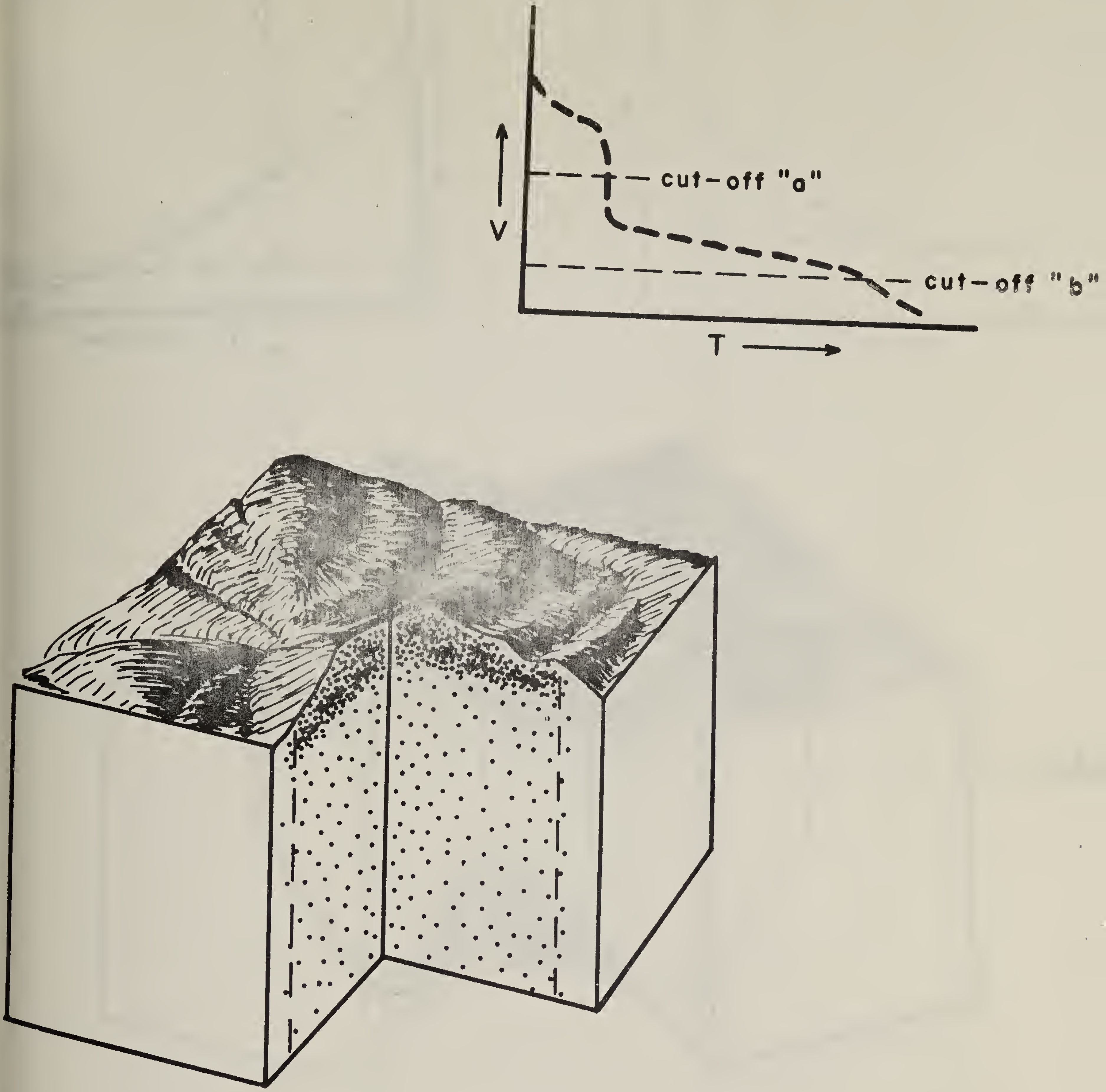
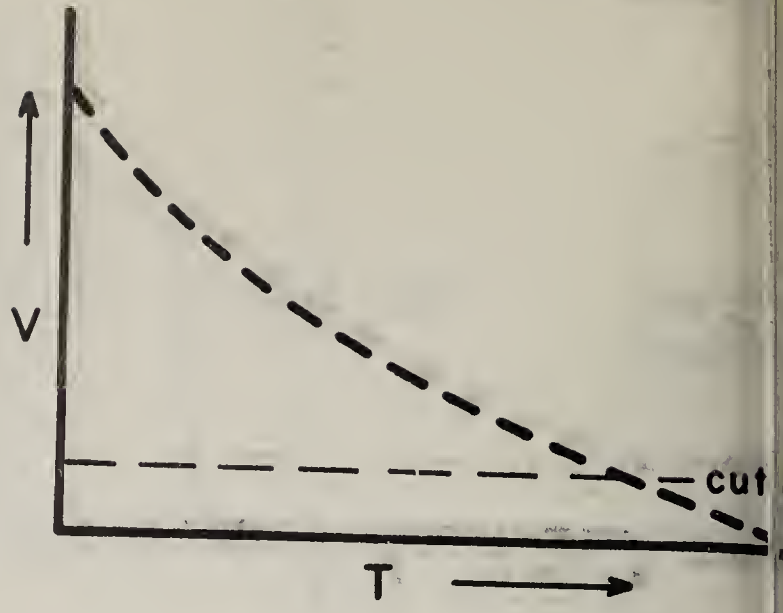


Fig. 66 - An idealized representation of a disseminated mineral deposit with dispersed values but rlain by an enriched zone. As improved technology and/or rising prices enable profitable extraction of underlying, lower-grade rock, the reserve tonnage is increased substantially.



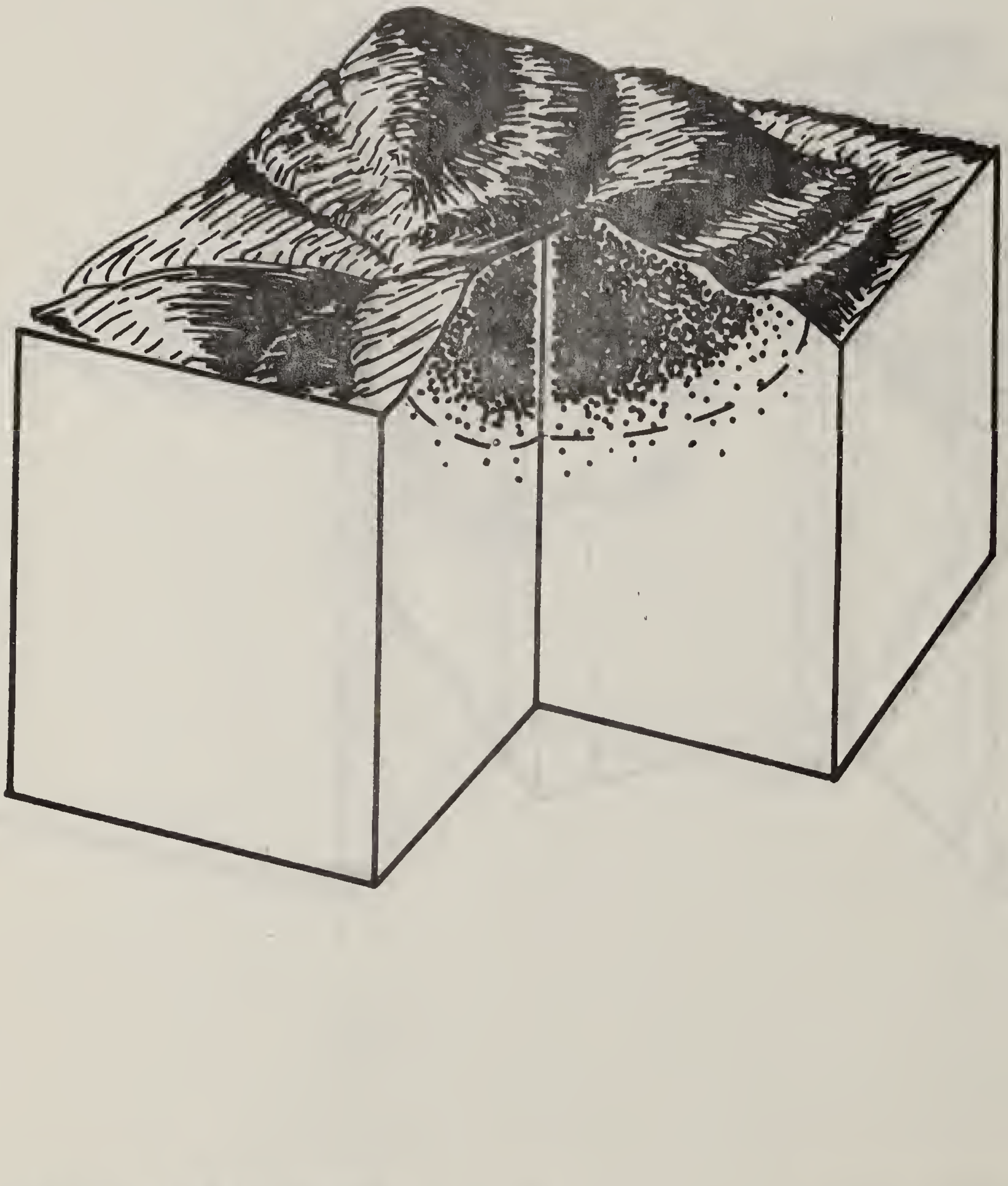


Fig. 67 - An idealized representation of a mineral deposit with a high-grade center grading outward into lower-grade material. Exposure of the surface as well as a regular shape continuity of values would make the costs of mining such a deposit relatively low, thereby lowering the cutoff grade and yielding a comparatively high reserve tonnage.

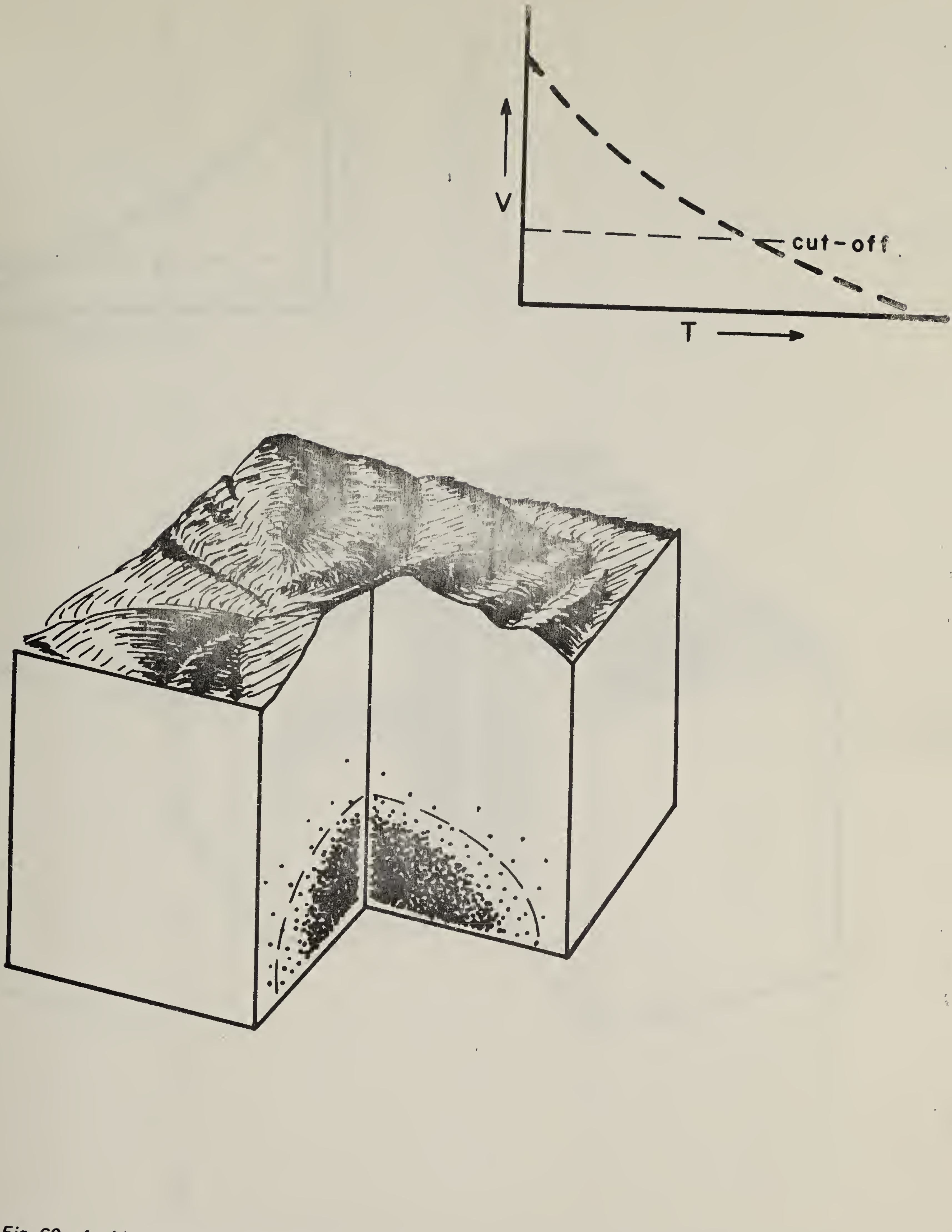


Fig. 68 - An idealized representation of a mineral deposit with a high-grade center grading outward to lower grade material. Although similar to the deposit represented in the preceding illustration, the position of this deposit at depth would increase mining costs and thereby raise the necessary cutoff grade, resulting in a smaller ore reserve tonnage, even though the two deposits might otherwise be identical.

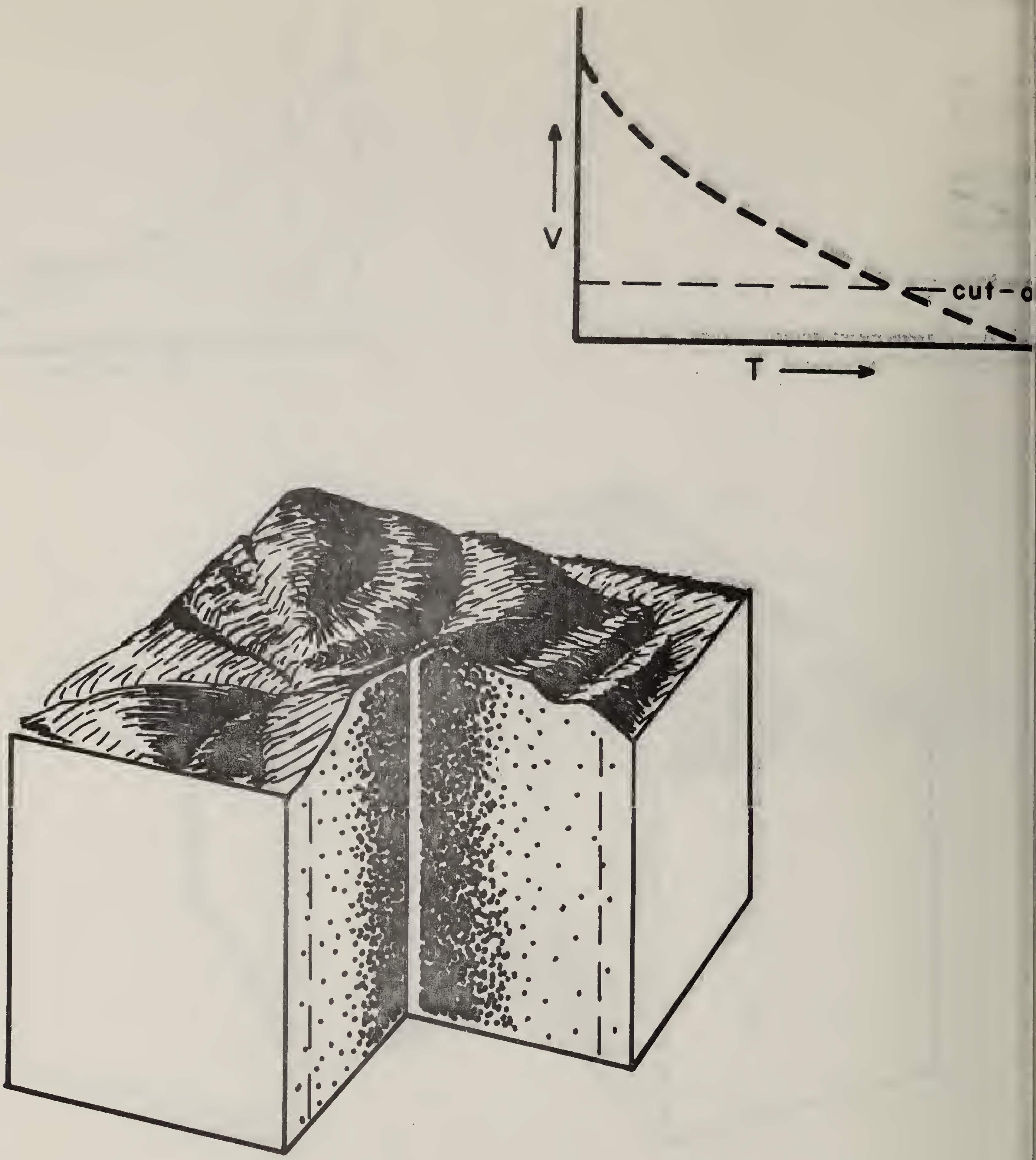


Fig. 69 - An idealized representation of a disseminated mineral deposit with a long vertical dimension and a higher grade core with diminishing values dispersed away from the core. Small variations in the economic grade could have relatively large effects on the total reserve tonnage, particularly at depth.

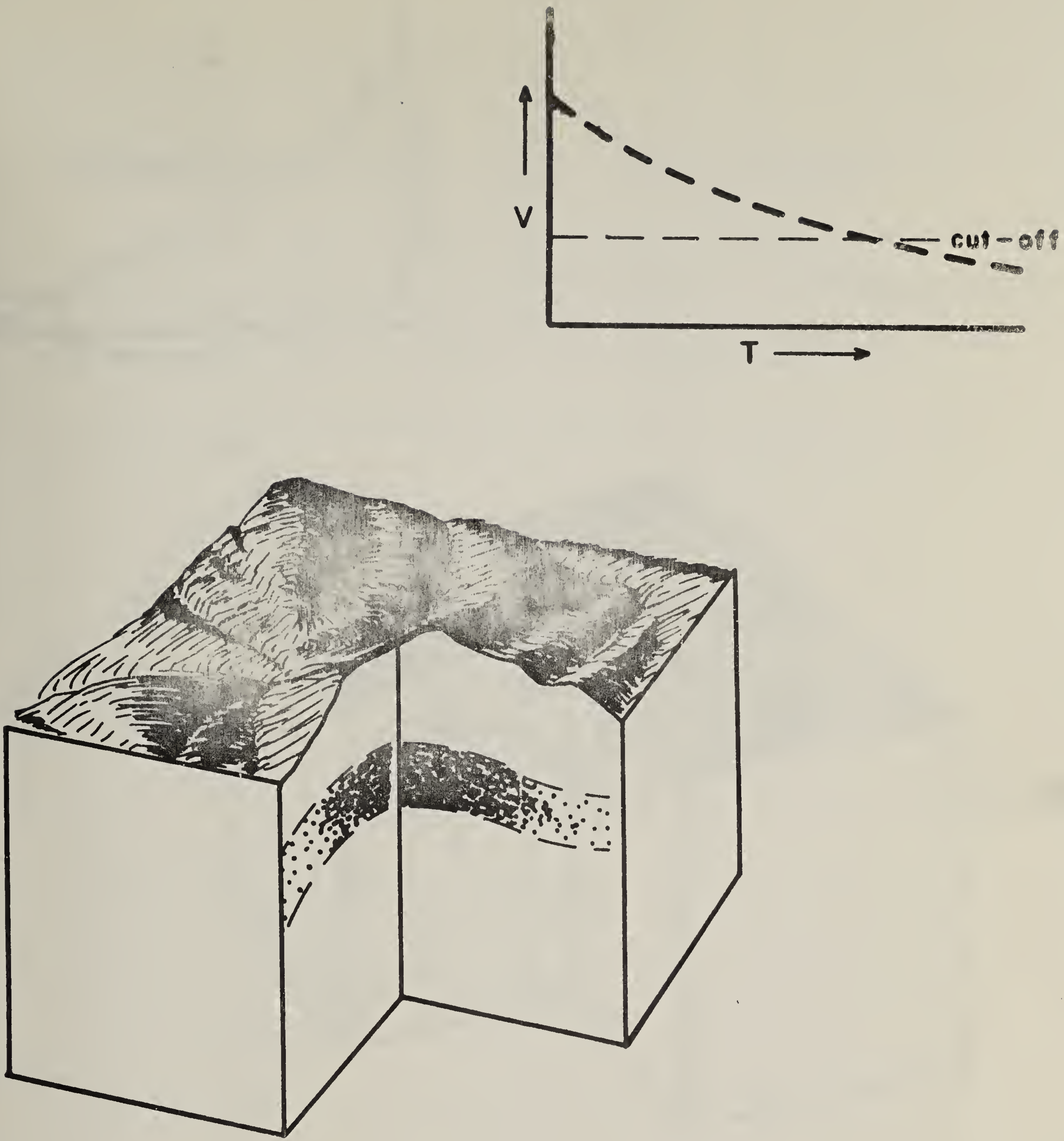
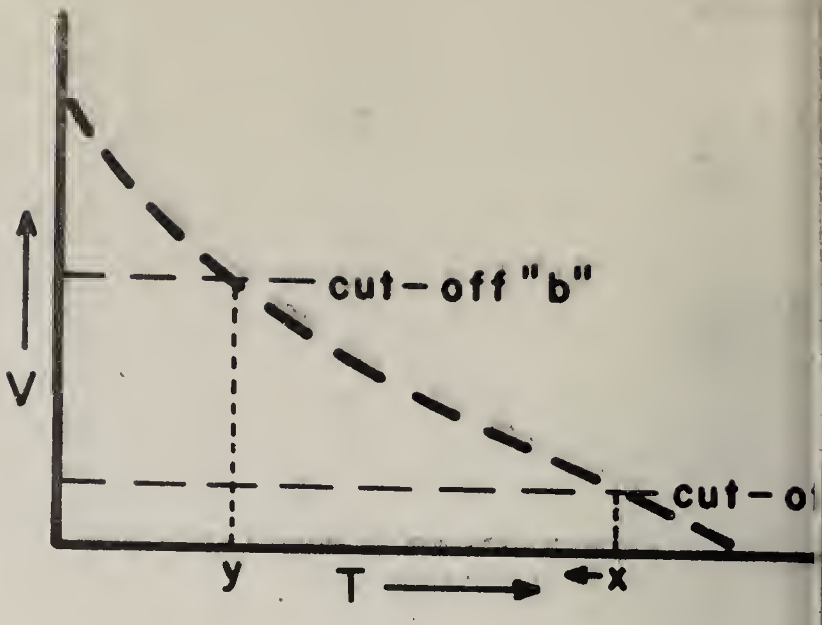


Fig. 70 - An idealized representation of a disseminated mineral deposit with greater horizontal dimensions, i.e., in a bedded form. Minor changes in cutoff grade could have relatively large effects on the total reserve tonnage.



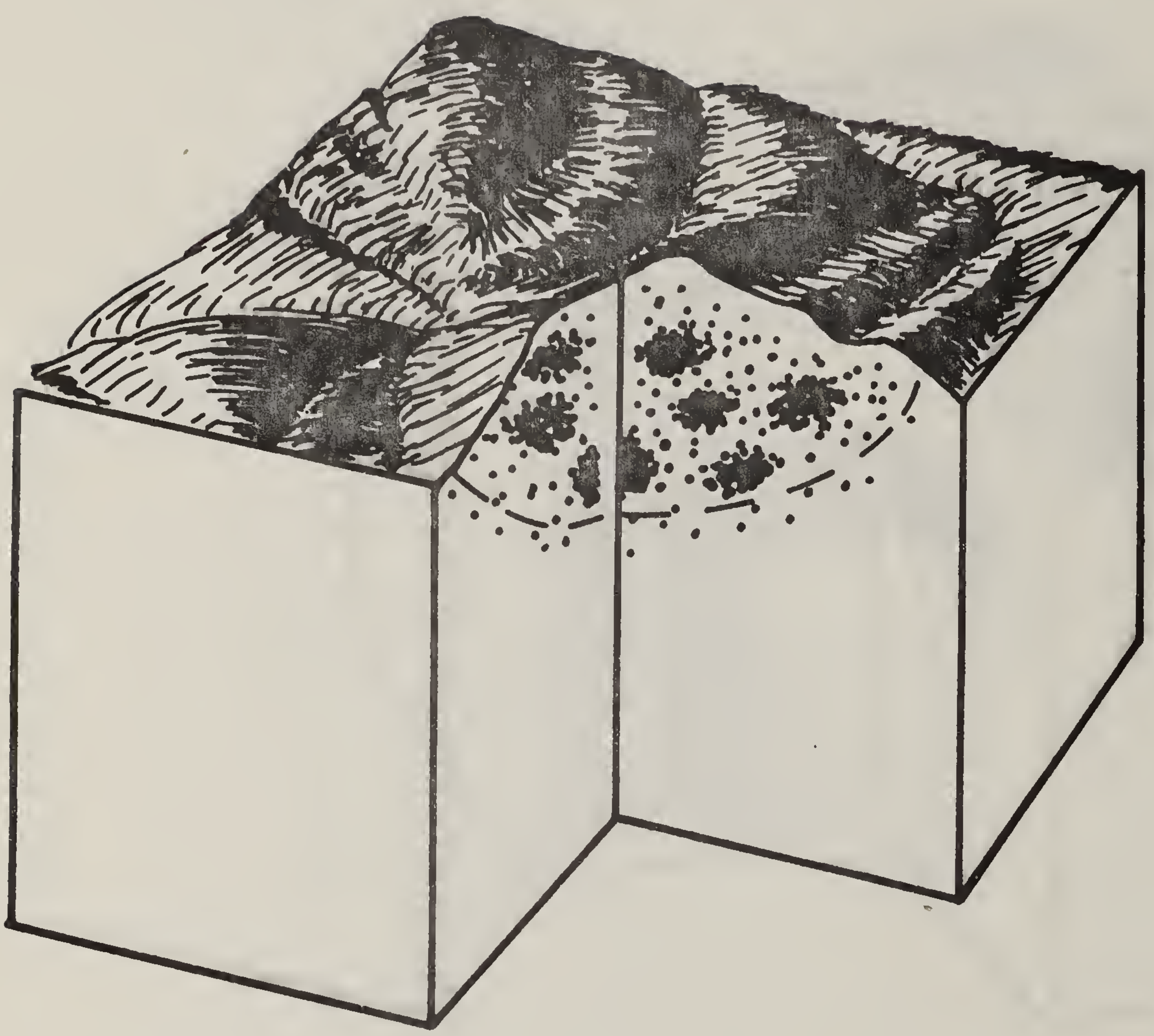
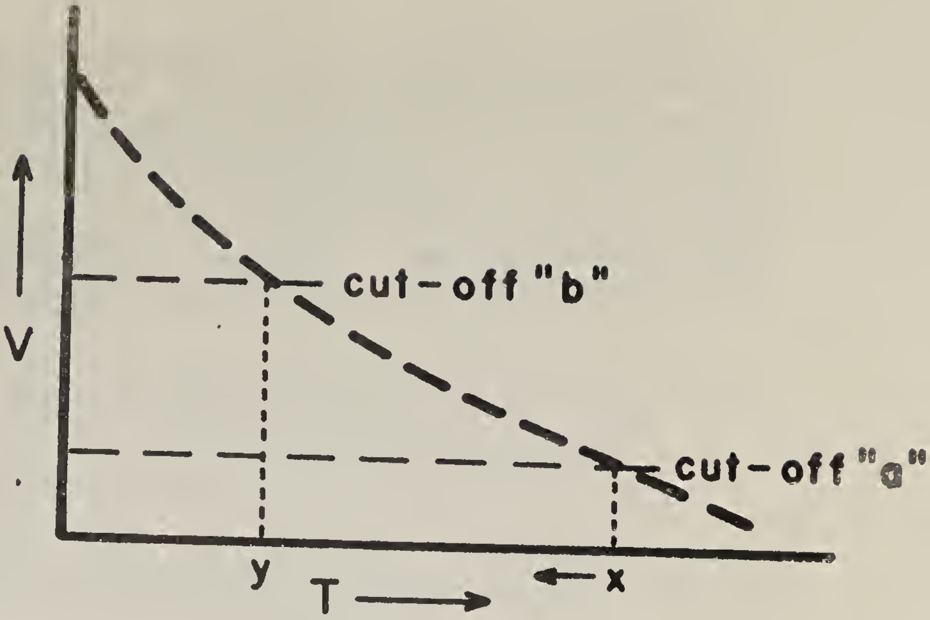


Fig. 71 - An idealized representation of a disseminated mineral deposit with higher values in isolated pockets. Small changes in cutoff grade could cause major changes in both total reserves and mining methods used. Many early bonanza deposits were actually of this type and improved technology by lowering costs has turned the intervening low-grade rock into ore.



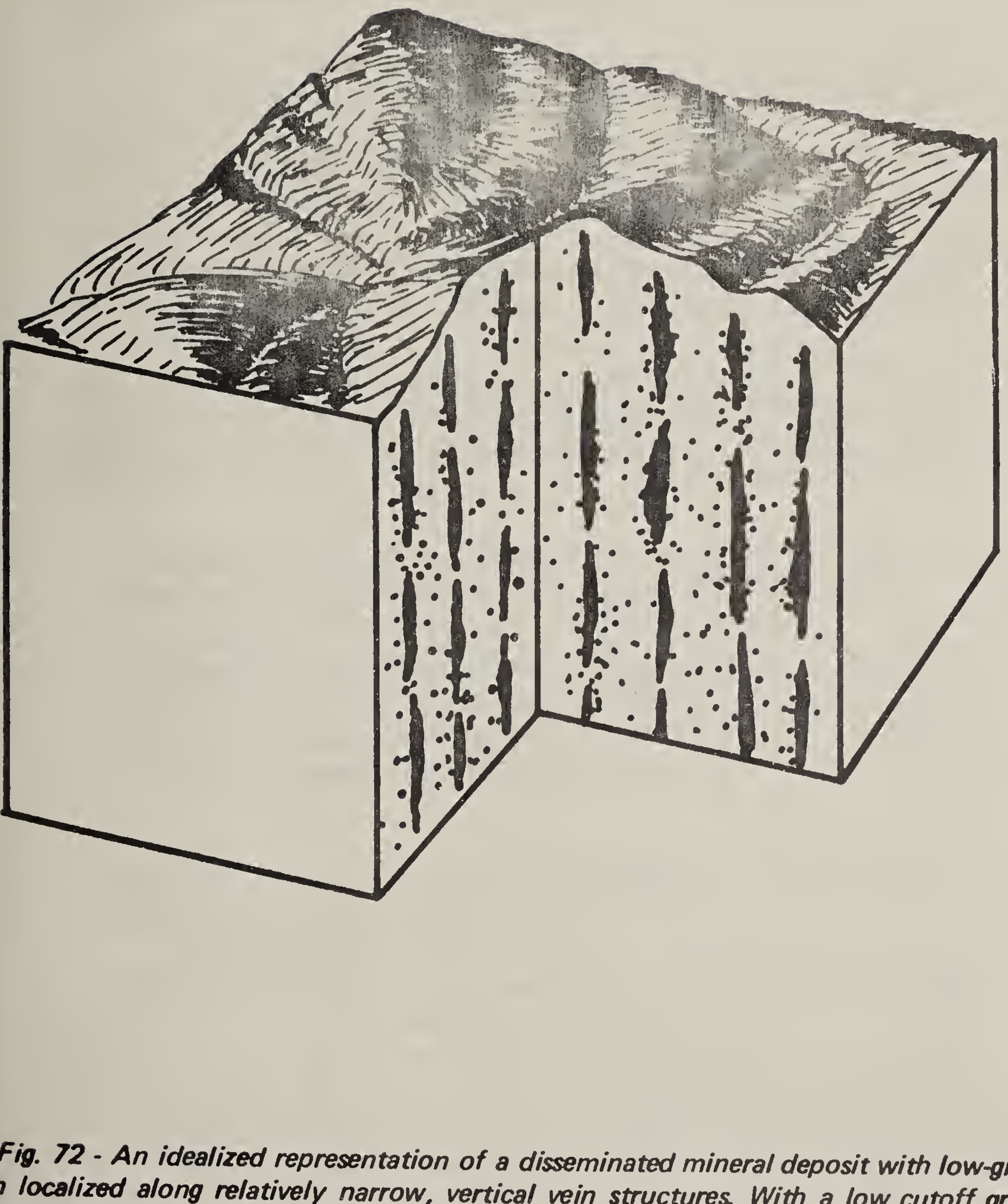


Fig. 72 - An idealized representation of a disseminated mineral deposit with low-grade values that have been localized along relatively narrow, vertical vein structures. With a low cutoff grade, the entire mass would become part of the ore reserve, but an increase in the necessary cutoff grade would make only the veins mineable and would severely diminish the total reserve tonnage. Many existing metallic mineral deposits are of this type. Many industrial minerals deposits are similar except that the localized high-grade areas have a horizontal rather than vertical attitude.

Earliest methods of classifying and defining different types of ore reserves were based essentially on geologic or other physical criteria rather than economic. Perhaps it would be more accurate to say that geologic factors were considered variable while economic factors were considered fixed, and early ore reserve estimates were thus applicable only for a given point in time. Of all the early systems of ore reserve classification, the oldest and perhaps most widely-used was composed of three categories. These were devised essentially for underground vein mines. As outlined by one prominent geologist, they were:

> *Positive Ore* or *Ore Blocked Out.* Ore exposed and sampled on four sides.
>
> *Probable Ore.* Ore exposed and sampled either on two or on three sides.
>
> *Possible Ore.* Ore exposed on only one side, its other dimensions being a matter of reasonable projection.[143]

These categories were really appropriate only to certain types of mineral deposits, however, and thus categories based on somewhat more flexible definitions were developed. As set forth by Hoover, these were:

> *Proved Ore.* Ore where there is practically no risk of failure of continuity.
>
> *Probable Ore.* Ore where there is some risk yet a warrantable justification for assumption of continuity.
>
> *Prospective Ore.* Ore which cannot be included as "Proved" or "Probable," nor definitely known nor stated in any terms of tonnage.[144]

The United States Bureau of Mines has developed a still further classification of ore reserves that is considerably more complex (and far more ambiguous) than the preceding classifications. Rather than *Proven, Probable,* and *Prospective,* the Bureau uses the terms, *Measured, Indicated,* and *Inferred,* defined as follows:

> "*Measured ore* is ore for which tonnage is computed from dimensions revealed in outcrops, trenches, workings, and drill holes, and for which the grade is computed from the results of detailed sampling. The sites for inspection, sampling, and measurements are so closely spaced and the geologic character is defined so well, that the size, shape, and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to differ from the computed tonnage of grade by more than 20 per cent.
>
> "*Indicated ore* is ore for which tonnage and grade are computed partly from specific measurements, samples, or production data, and partly from projection for a reasonable distance on geologic evidence. The sites available for inspection, measurements, and sampling are too widely or otherwise inappropriately spaced to outline the ore completely or to establish its grade throughout.
>
> "*Inferred ore* is ore for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposits and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition for which there is geologic evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred ore should include a statement of the special limits within which the inferred ore may lie."[145]

In essence, the various terms mentioned are used to describe the degree of assurance with which ore reserves may be stated. The most common terms may be summarized in probability or degree of assurance terms as follows:

Degree of Assurance
(in percent)

10 - 50	50 - 80	80 - 99
Possible or *Inferred*	*Probable* or *Indicated*	*Proven* or *Measured*

It should be noted that there is no 100 percent assurance of the existence of ore. As one authority has noted,

> Paradoxically enough, no one can be sure how much ore there is in a mine until it has been mined out; therefore, at best, ore reserve figures are estimates rather than certainties.[146]

Because the size of the ore reserves in a mineral deposit is dependent upon future conditions and events as well as upon existing but unknown conditions, the use of mathematical probability terms (whether referred to as likelihood or degree of assurance) becomes suspect and could be misleading. As a consequence, perhaps the use of McKinstry's and McLaughlin's suggested classifications and terminology is more appropriate. They have suggested three categories based on capacity for measurement.

Some orebodies can be well-defined almost from the start, but in many deposits the limits of ore are rarely known until all ore has been extracted. McKinstry, quoting McLaughlin,[147] sets up three classes:

> I. *Plenemensurate orebodies* – those capable of being fully measured and sampled at an early stage in the operations.
>
> II. *Partimensurate orebodies* – those in which prospects for ore in addition to proved reserves remain a substantial element until the later stages of the life of the mines based on them.
>
> III. *Extramensurate orebodies* – those difficult to explore and measure much in advance of mining, in which the value of prospects for ore based on geologic evidence exceeds the value of proved reserves throughout most of the life of mines supported by them.

Other terms are also used with respect to the material found within a mineral deposit. It is common practice to classify ore reserves by grade (i.e., by percentage of product content) and to maintain maps showing the location and extent of reserves of different grades. Three other major classifications are often used, with subdivisions by average grade in each class. The first is ore and includes only rock which is ore-grade except under sudden and severe adverse conditions (significant price drops or cost increases). The second includes marginal rock (or ore) which is barely ore-grade or becomes ore-grade under occasionally more favorable conditions. The third is low-grade or *protore,* which is too low in value content to be mined without a sharp increase in the price/cost ratio. Major technological advances or very large price increases are usually necessary to change *protore* to *ore.*

At operating mines it is also common to classify the mineral mined as either *ore* or *waste,* the former being of sufficient value content to permit economic extraction of that content while the latter contains an insufficient value content. At some properties and for some commodities, several categories of ore are used depending upon the extractive process used. This is common in the utilization of phosphate minerals where several grades of rock containing phosphate may be mined from a given deposit, each grade destined for a different use. The same is also true at many large copper deposits where ore destined for normal beneficiation and smelting is segregated from rock from which the copper is to be extracted by leaching. The criteria used in making these classifications change with both physical and economic conditions.

In the more than two decades since the end of World War II, another term with respect to mineral reserves has crept into the literature. This is the term, *resources,* used in a specific and not a generic sense. As sometimes used, *potential reserves* or mineral *resources* include mineralized rock of too low grade to become ore at current prices and potential reserves whose existence may simply be postulated in areas of known mineralization, but for which there is no direct evidence of their existence. Past estimates of United States reserves of various mineral commodities have, for the most part, included all categories of reserves and, in some cases, have also included this concept of resources.

The term *resource* implies, in the generic sense, something that is available and can be put to use within a reasonable period of time. However, the term as used in various tabulations and discussions of the nation's mineral wealth has referred to potential reserves which are not ore now but which *may* become so at some date in the distant future, or which are available as by-products of other mineral mining only. The same term has also been applied to potential ore reserves which are assumed to exist but which have not yet been found. Thus, these so-called "resources" may or may not be available for the nation's utilization in the future. In fact, they may not even exist.

The various classifications of ore reserves have all been based for the most part on the extent of man's knowledge about those reserves. The extent of his ability to take action with respect to his knowledge should also be considered. Thus, all mineral commodity reserves may be said to consist of two categories: *responsive* reserves, whose production can be varied according to demand, and *non-responsive* reserves, from which production rates are more or less fixed or are dependent upon variables other than specific demand for the commodity involved. By-product and co-product reserves, which are usually included in the total mineral reserves listed by various sources, are normally non-responsive reserves. Their utilization is dependent upon demand for other minerals with which they are associated. For example, the production of by-product silver from copper ore normally varies with the demand for copper, not for silver. The silver content of known copper reserves thus form a non-responsive reserve of silver.

Approximately one-third of gold, molybdenum, and tungsten and two-thirds of silver production is from ores in which these metals are by-products. Lead may be a co-product or by-product of zinc ore, and vice-versa, depending on the particular mineral deposit. Most of the nation's molybdenum, lead, and zinc reserves are contained in deposits which are responsive to demand, however, despite their partial production as by-products. On the other hand, approximately one-half or more of the domestic reserves of gold, silver, and tungsten are tied up as by-products in the ores of other metals.

Of all of the concepts involved in mineral reserve estimates, that they are estimates is probably the most important. As such, the one definite fact about them is that they are most assuredly wrong. How far wrong they may be can only be shown by subsequent events. In the past, some have been extremely far from the truth.

Waldemar Lindgren[148] pointed out in 1902 two of the principal errors that are repeatedly made in estimates of mineral resources. In 1877, Professor Suess[149] in Vienna, and in 1880, Mr. A. Del Mar[150] predicted in their works on precious metals that the output of gold would gradually decrease, that there was scarcely any hope for further discoveries, and that the metal would not be able to maintain its economic importance. In 1880, United

States gold production amounted to about $33 million. By 1900 it had risen to about $79 million. In reviewing the predictions of Suess and Del Mar, Lindgren pointed out two principal errors in their thinking:

> In the first place the lands of the world were deemed to be so well prospected that no further discoveries were probable, and the second error lies in the failure to anticipate the possibliity of new processes for gold retraction and the utilization of vast reserves of low-grade ore bodies.

More recent estimates have been guilty of similar assumptions.

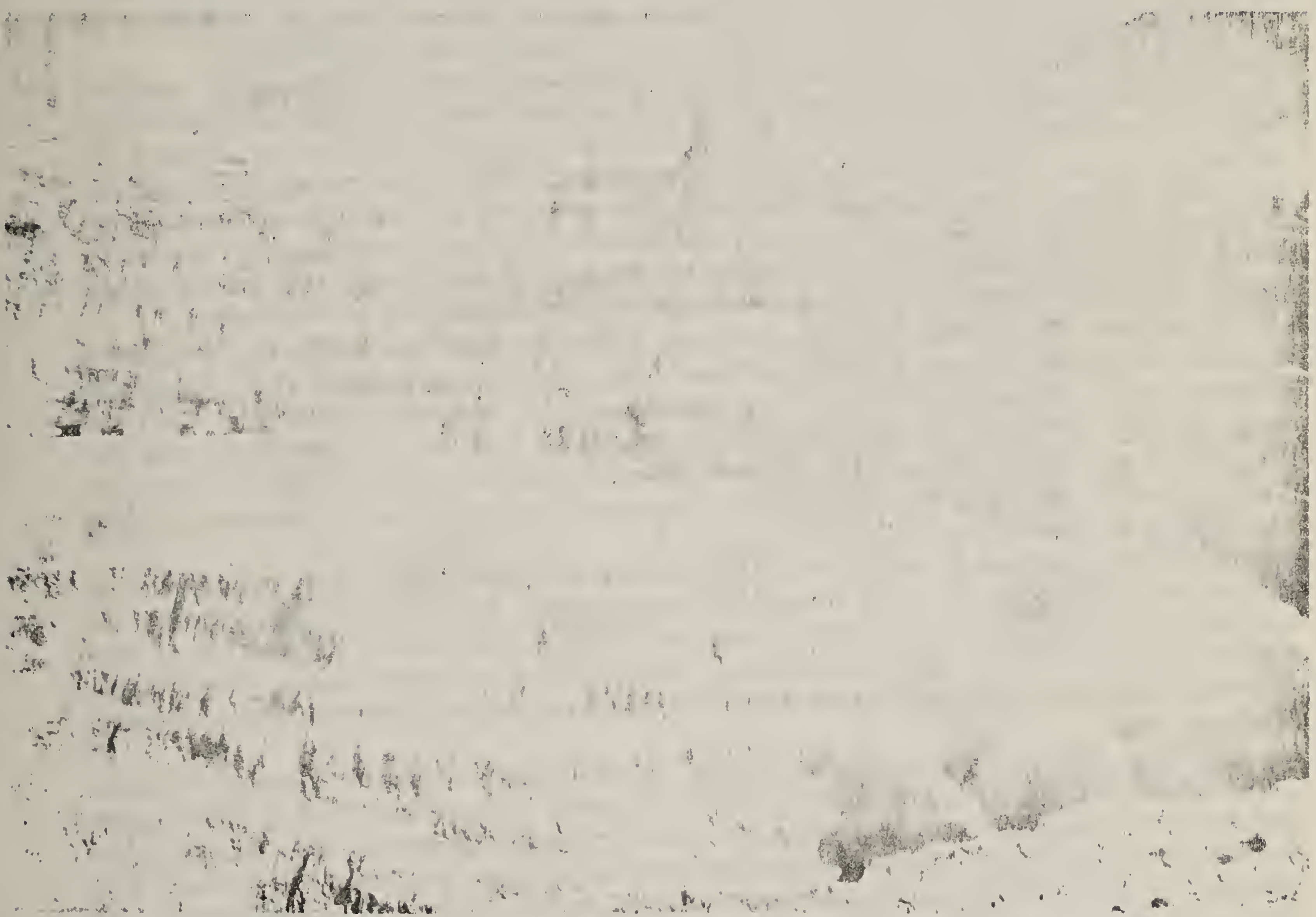


Fig. 73 - The Berkeley Pit at Butte, Montana, where modern, large-scale, low-unit-cost mining methods have permitted the utilization of large volumes of low-grade copper ore associated with veins of high-grade. Originally, only the veins, with their relatively high copper content were considered to be ore.

B. INDIVIDUAL PROPERTY ESTIMATES

1. Metalliferous Properties

Many of the factors contributing to inaccuracies in total reserve estimates mineral commodities have been pointed out. Estimates vary at individual properties for similar reasons. Incomplete data, irregular distribution of ore, mine fires and cave-ins, and variations in price all lead to changes in ore reserve estimates.

At Bisbee, Arizona, for example, reserve estimates for specific copper orebodies have proven, on the average, to be reasonably close to the amount of ore subsequently extracted. It is too expensive, however, to fully delineate individual orebodies, and estimates are made by projection based on geologic information, drill hole intercepts, and exposures in underground workings. As shown by subsequent mining, the ore pinches out short of its projected limits in some cases, and in others it extends farther than anticipated.

Many of the orebodies at Bisbee consist of large masses of solid iron and copper sulfides. Some of these massive sulfide bodies have been in a critical chemical and physical state such that, upon exposure to air by mine workings, they have caught fire and had to be sealed off. Although the ore is still there, for practical purposes, it is lost and reserves consequently have been reduced. In addition, the enclosing rock at Bisbee is often soft and incompetent in areas containing a heavy concentration of orebodies. Mining is consequently retarded by persistent cave-ins which sometimes become so frequent or serious that the ore cannot be profitably extracted and the area is abandoned, with the resulting loss of ore reserves.

In another, and perhaps extreme, example, drilling by a mining company (Continental Materials) south of Tucson, Arizona, outlined a copper-lead-zinc orebody that appeared to contain several million tons of ore. Thus encouraged, the company sank a deep shaft and began mining. After considerable development work had been done, it was discovered that the drill holes had actually each intersected a series of small ore pods separated by extensive areas of waste (see Figure 74). Most of the estimated ore reserves were non-existent, causing the mine to be closed down in 1968.

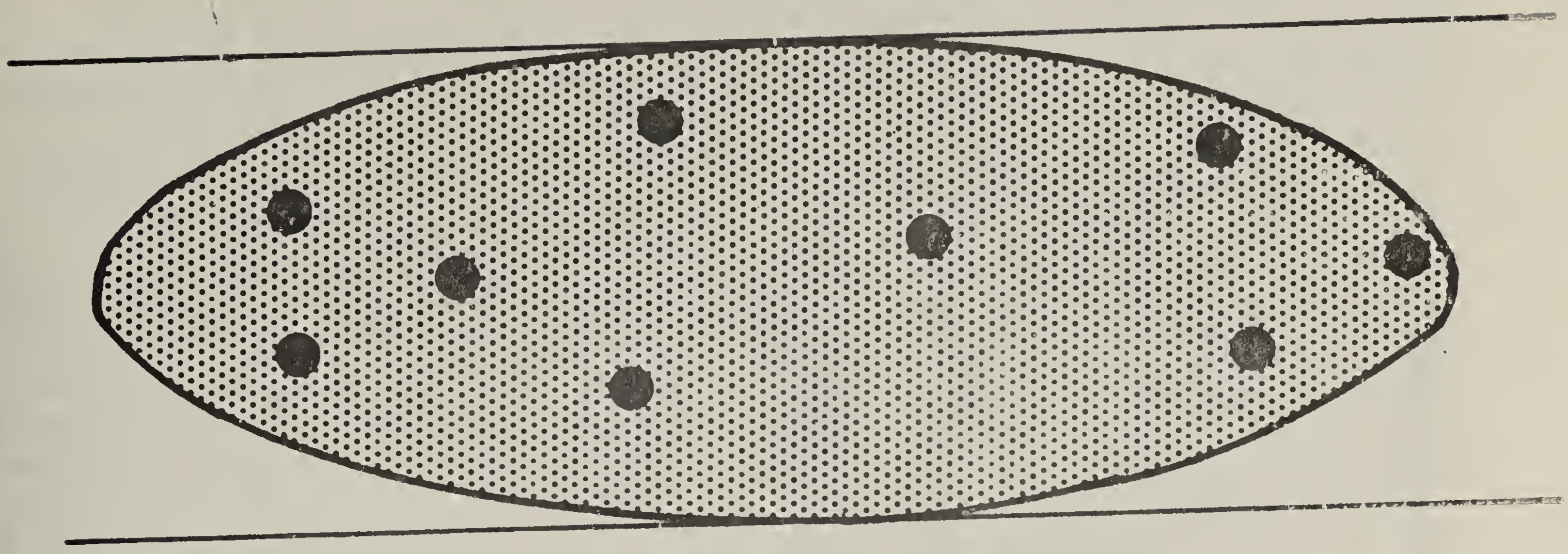
In just the opposite situation, a gold placer deposit in Northwest Alaska contained only coarse gold fragments averaging about 0.9 ounces each, but no fines. In exploring the deposit, more than 400 holes, each four inches in diameter, were drilled through the 15 foot thick deposit. None of these exploratory holes showed any gold values. Nonetheless, dredging operations produced an average of $1.75 worth of gold from each yard of gravel worked.

Ore has a very spotty distribution in many precious metal and mercury mines. Veins at Terlingua, Texas, contained randomly distributed, small, high-grade streaks of mercury ore separated by varying amounts of low-grade rock and waste. The distribution of ore was too irregular to be outlined by drilling, and reserve estimates were frequently proven to be too low or too high. Mining could not be practically limited to individual ore streaks, and whether a given block of ground was ore or waste depended on the number of high-grade streaks found by mining in the block (see Figure 75).

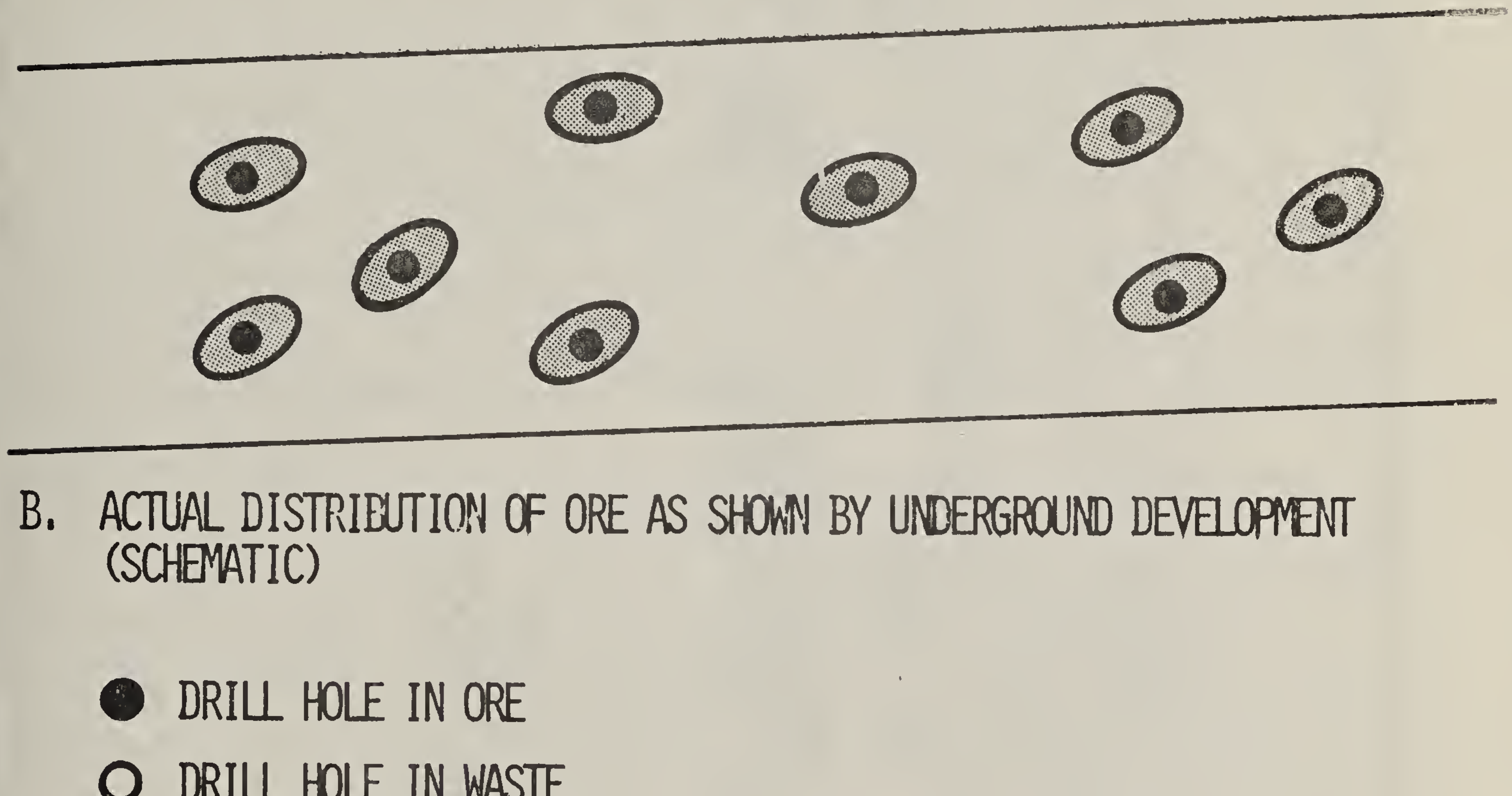
In massive, low-grade metalliferous deposits, it is common for the size of reserves to change with changes in the price of the product and with changes in technology. Thus, what may be an orebody of a specific size one day may be much larger or much smaller the following day. The Pima and Sierrita copper deposits in Arizona are excellent examples of such an expansion. The Deep Ruth copper orebody in Nevada is another example of lost ore reserves "destroyed" by high costs. The taconite deposits of Minnesota are perhaps an even better example of the changes that can occur in individual property mineral reserves as the result of changing economic and technological conditions.

2. Industrial Minerals Properties

Factors affecting reserves and grades in industrial mineral deposits include geologic structures (faults, fractures, folds), stratigraphy (continuity and thickness of beds), chemical



A. PRE-DEVELOPMENT ORE ESTIMATE FROM DRILL DATA (SCHEMATIC)



B. ACTUAL DISTRIBUTION OF ORE AS SHOWN BY UNDERGROUND DEVELOPMENT (SCHEMATIC)

● DRILL HOLE IN ORE

○ DRILL HOLE IN WASTE

Fig. 74 - Plan view of a vein containing relatively small pockets or "shoots" of high-grade ore in a matrix of relatively low-grade material. The attitude, shape, and depth of the deposit require a high cutoff grade, making the intervening material waste rather than ore. Inaccurate interpretation of data from drill holes in this deposit made the high grade appear continuous rather than erratic.

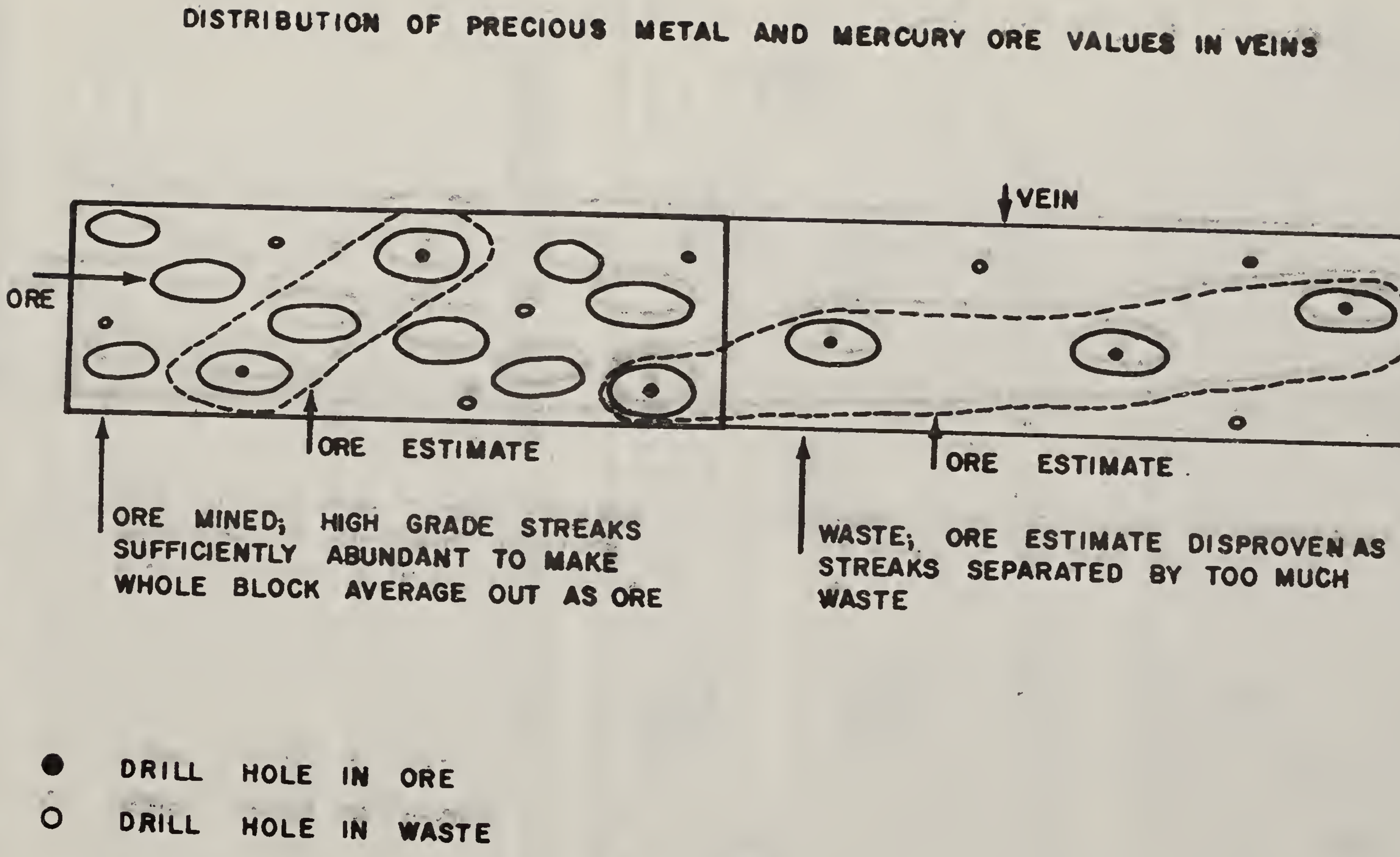

DISTRIBUTION OF PRECIOUS METAL AND MERCURY ORE VALUES IN VEINS
VEIN
ORE
ORE ESTIMATE
ORE ESTIMATE
ORE MINED; HIGH GRADE STREAKS SUFFICIENTLY ABUNDANT TO MAKE WHOLE BLOCK AVERAGE OUT AS ORE
WASTE; ORE ESTIMATE DISPROVEN AS STREAKS SEPARATED BY TOO MUCH WASTE
● DRILL HOLE IN ORE
○ DRILL HOLE IN WASTE

Fig. 75 - Idealized representation of mercury-bearing mineral deposits in West Texas. Although individual ore mineral pockets in such a deposit may be of sufficient grade to be considered ore, excessive amounts of lower-grade rock between them may make the entire deposit economically unattractive. The same concept also applies to precious metals and some other high unit value minerals.

composition, and physical characteristics such as grain size, angularity, cleavage, hardness, and color. The original distribution, thickness, continuity, and chemical and physical qualities of industrial minerals deposits have in many (if not most) instances been changed by later geologic events. The characteristics of these deposits, both original and modified, are non-uniform. The mere existence of a deposit (limestone, gypsum, potash, perlite, etc.) over a large area does not guarantee that the deposit is everywhere of sufficient size, grade, and accessibility to be considered "ore." Correspondingly, since only portions of the total deposit may be of economic value, it is incorrect and illogical to label any such deposit a "common rock" simply because of the widespread occurrence of the host rock. There really is no such thing as a "common" rock. Virtually all specific mineral deposits and their host rock formations differ in one form or another.

As an example, reserves of chemical grade limestone were developed by the Sunrise Mining Company in 1959-1960, southeast of Tucson, Arizona, in the Empire Mountains. Large areas of this particular limestone are almost pure calcium carbonate. Drilling and surface sampling of the deposit confirmed its generally high quality. Nevertheless, iron, magnesium, and other impurities also occur in variable amounts throughout this particular limestone deposit. The iron and manganese oxides and silica tend to be concentrated adjacent to zones of fracturing and faulting, the locations and extent of which are not predictable from surface exposures. The various impurities are not confined to distinct beds or zones which could be readily outlined.

Estimated reserves for this limestone deposit are in excess of 40 million tons. It was concluded, however, that limestone reserves of specific calcium carbonate grades requiring close tolerances could not be defined far enough in advance of mining because of the erratic distribution of the impurities and the necessity for detailed sampling at the working faces. Known reserves would thus probably not exceed 5,000 tons of suitable limestone at any one time and the total potential reserve would be unknown.

A gypsum deposit located a few miles west of the limestone deposit described above was also explored by Sunrise Mining Company during the same period. Limited surface outcrops indicated a continuous band of gypsum extending along the side of a mountain for several thousand feet. Subsequent drilling and bulldozer cuts spaced at suitable intervals showed that the gypsum lay in a series of thin, discontinuous, lenticular bands which had been extensively dislocated by faults. Furthermore, part of the gypsum had been converted to anhydrite (essentially, gypsum which has lost its water content), which is of much less value and utility than gypsum.

Preliminary ore reserve estimates based on surface exposures were reduced following this more detailed exploration work, as the continuity and quality of the deposit was shown to be less than initially anticipated. Reasonable projections based on the new information indicated "probable" reserves in excess of one million tons and "possible" reserves of two million tons or more. The nonuniform distribution of the gypsum lenses and uncertainty as to the extent of anhydrite replacement, however, precluded accurate estimates of grade and tonnage until additional closely-spaced drilling and sampling could be done. Once mining were initiated it was estimated that possibly as much as five to ten thousand tons of "assured" reserves of a specific grade could be maintained through sampling of the working faces and correlation with drill hole data.

The anticipated high cost of detailed reserve estimation and the reduction in reserves from preliminary estimates prompted additional exploration in not-too-distant areas. This additional exploration was successful in locating new gypsum deposits containing larger reserves of greater continuity. Thus, the original deposit remains only a potential reserve, while other, better-known reserves were acquired. Faick[151] has described some of the problems in quality determination of pozzolanic materials which are natural or artificial materials added to mortar or concrete to produce a product of specific characteristics, usually at a lower cost than otherwise possible.[152] Siliceous sediments, volcanic tuff, and pumice are common sources of pozzolans, and these are of wide occurrence in California. Pozzolanic materials must, however, be free of or very low in chemical components which have deleterious effects on concrete or mortar, and they must be high in beneficial components. Excess alkali or basic constituents of a reactive nature as well as contained water may render the material useless. The pozzolan rock must have a high content of silica in the form of volcanic glass or certain silicate minerals. In the development of deposits with desired pozzolanic properties much is heavily contingent upon local conditions and geologic history.[153]

Despite the widespread occurrence, then, of potential pozzolanic material in California, deposits of economic value are limited in occurrence. Chemical analyses must be made of any prospective material, and it must be tested by actual use in concrete or mortar before its value can be determined. Such investigation is costly and requires extensive sampling of potentially valuable sections of a mineral deposit. Mere chemical analysis is insufficient as it is the state of reactivity of the minerals in the rock which determines its usefulness as a pozzolanic material. In any one deposit, *inferred* reserves of pozzolans could be quite large, but the necessity of close quality control would keep proved reserves to a few thousand or tens of thousands of tons at any one time.

Perlite is a particular type of water-rich volcanic glass having properties of expansion under heat treatment. The treated material is valuable for use in light-weight aggregate and as thermal and acoustical insulation. It is found in many areas of the West. Deposits of perlite are of particularly widespread occurrence west and south of Superior, Arizona. The mineral composition and physical behavior of the perlite varies, however, from place to place. Only in a few areas does the perlite have the properties of sufficiently high expansion and response to heat treatment to make it valuable. Some of the perlite is sandwiched between other rock formations, and it is variable in thickness, so that it cannot be profitably mined by open-pit methods at the present time. Present mining activity is restricted to a small area of the total deposit that is amenable to open-pit mining which contains high-expansion perlite. Total perlite reserves in the Superior, Arizona, area are estimated to exceed a hundred million tons. Total known useable reserves are a few million tons at best, and are subject to change depending on local variations in quality of the perlite.

Similar conditions exist in the limestone deposits of California, particularly in those that are suitably located for cement production. Because many of the California limestone deposits are localized roof pendants imbedded in granitic intrusions, the magnesium oxide content of the limestone in a given deposit is usually quite variable. The presence of magnesium impurities is thus unpredictable and necessitates close sampling ahead of production. The capricious occurrence of magnesium in the limestone has caused particular problems at San Andreas and at Redding in Northern California. At San Andreas, a sizeable reduction in previously estimated ore reserves was caused by the irregular presence of excess magnesium oxide.

Other examples of the changes in ore reserves made necessary because of the variable physical features of mineral deposits, both metallic and non-metallic, are legion. To these must be added the changes caused by the changing technology of extraction and utilization and by changing economic conditions. All of these combine to make the accurate estimation of the total reserves in a particular mineral deposit virtually impossible. When such estimates are expanded to a regional or national scale, their potential for accuracy becomes even less.

C. NATIONAL MINERAL RESERVE ESTIMATES

1. Base Metals Reserve Estimates

Since the years immediately following the end of World War II, a number of estimates have been made and published for reserves of various mineral commodities in the United States. These estimates have used various concepts of mineral reserves, but virtually all have included *inferred* or *possible* ore as well as those more accurately determined amounts.

One of the earliest of these studies to estimate the nation's mineral reserves was the so-called *Paley Report* published in 1952. This report, which has come to bear the name of the chairman of the group responsible for it, was actually the report of the President's Materials Policy Commission, titled *Resources for Freedom.* The second volume of the Commission's report, titled *The Outlook for Key Commodities,* is actually the critical volume which contains the principal mineral reserve estimates. Although among the earliest of the postwar national minerals reserve estimates, the *Paley Report* is probably still the best known and has had considerable impact upon federal minerals policy ever since its publication in the early 1950's.

The *Paley Report* did not attempt to make estimates for all minerals, but was concerned primarily with base metals and other commodities critical to the nation's defense. Dated as of 1950, the *Paley Report* estimated the nation's reserves of iron ore at 79 billion long tons containing 25 percent or more iron, but only four billion long tons containing 35 percent or more iron. Although these reserve estimates were made in 1950, from 1951 to 1967, production of iron in the United States has totaled more than two billion long tons, virtually all of it higher in grade than 35 percent iron.

Table 11 lists several other domestic iron ore reserve estimates that have been made since the *Paley Report.* The type of reserves (*measured, indicated, inferred, potential*) and grade were not given in each case, preventing direct comparison between all of the estimates. The variations in the *Mineral Facts and Problems, Paley,* and *Carr* estimates of domestic iron ore of plus 22-25 percent iron content reflect individual assumptions, which were at least partly subjective, as to how much ore can be inferred from available data. Actual production during the 1950-1955 period was insufficient to account for the variations in these estimates. The 1967 and 1968 reserves listed by the *Commodity Data Summaries* is apparently only *measured* plus *indicated* and as such would imply a substantial transfer of reserves from the *inferred* class to the *measured* and *indicated* categories since 1950. Furthermore, new orebodies have been found since in both the Western and Eastern United States, and reserves have been added to by continued development in existing mining districts.

Prior to 1964, Minnesota, the nation's major (59 percent of domestic useable iron ore production in 1965) iron producing state, maintained taxes upon iron mines which became increasingly burdensome, causing many higher cost mines to shut down. The state has since modified its tax policies and some mines have been brought back into production, and several new properties opened. The sharp increase in the *Commodity Data Summaries'* ore estimates from 4.0 to 5.5 billion long tons to 15 billion long tons in 1968 may be partly due to a change in Minnesota's mining taxation policies, permitting more extensive development of *measured* and *indicated* ores.

The production of iron ore from 1951 through 1966 in the United States amounted to a little more than two billion long tons (of which 1.41 billion long tons were useable, having less than five percent manganese content), and was more than compensated for by the discovery and development of new reserves. In recent years, approximately one-third of the iron ore consumed in the United States has been imported,[154] and from 20 to 30 percent of total iron consumption has been supplied by scrap. Canada provided 55 percent of the nation's iron ore imports in 1962-1965. Increasing exhaustion of domestic high-grade iron ore reserves, however, has caused a shift in the production of low-grade taconite ores which are beneficiated to higher-grade pelletized material before going to the iron and steel furnaces. The use of taconites has thus increased total reserves.

Table 11

ESTIMATES OF IRON ORE RESERVES IN THE UNITED STATES

Date	Source	Ore Reserves (in billions of long tons)	
1950	(MF&P)	10.694	(1.169 *measured,* 3.365 *indicated,* 6.16 *inferred)*
1950	(MF&P)	67.0	(25 percent or better iron content *measured, indicated,* and *inferred)*
1950	(Paley)	79.0	(25 percent or better iron content in total reserves)
1950	(Paley)	4.0	(35 percent or better iron content)
1955	(Carr)	70.2	(22 percent or better iron content in total reserves)
1955	(Carr)	5.5	(36 percent or better iron content)
1962	(Min. Res.)	5.5	
1967	(CDS)	15.0	(25 to 60 percent iron content)
1968	(CDS)	15.0	

Sources: MF&P = Mineral Facts and Problems, U.S. Bureau of Mines
CDS = Commodity Data Summaries, U.S. Bureau of Mines
Paley = President's Materials Policy Commission (*Paley Report)*
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
Carr = "Iron in the United States" *Mineral Resource Investigations*

Production and consumption of iron ore have varied widely from year to year. While consumption has generally risen, production trended downward until 1959. Since then, however, the trend of domestic production has been increasing. Projected 1985 consumption of iron ore ranges from 117 to 143 million long tons, and production ranges from 100 to 130 million long tons. According to the 1968 *Commodity Data Summaries'* reserve estimate of 15 billion long tons of iron ore, present reserves are sufficient to supply a constant annual consumption rate of 150 million long tons for 100 years. Competition from foreign sources will, however, probably hold down domestic iron ore production to a lower figure than that required to satisfy a total demand that will undoubtedly increase.

As of 1950, the President's Materials Policy Commission estimated that the nation had approximately 25 million short tons of copper in ore, including *measured, indicated,* and *inferred* reserves at an average grade of 0.9 percent copper. By 1967, the nation's copper mines had produced more than 17 million tons of copper and still had, according to the *Commodity Data Summaries,* published by the United States Bureau of Mines in 1967, more than 85 million tons of copper in ore averaging 0.8 of one percent copper. Although production in the period from 1961 to 1967 totaled nearly three-quarters of the 25 million ton reserve estimated in 1950, reserves had actually grown by more than three times as much as the 1950 estimates.

Several copper metal reserve estimates are listed in Table 12. As with iron ore estimates, the data are not directly comparable in all cases. Many of the estimates listed were derived from, or quotations of, previous estimates. The *Mining World* 1958 estimate apparently includes substantially lower-grade rock as ore than do the other estimates, inasmuch as the quoted figures are much higher. The *Commodity Data Summaries'* reserve estimates are evidently derived from earlier Bureau of Mines estimates (e.g., the 1964 total reserve estimate of 85.59 million tons, published first in 1967, which appeared in the 1968 *Commodity Data Summaries* as 85.5 million tons). Notwithstanding the inherent discrepancies of the various estimates, copper reserves have been substantially increased since 1951, more than compensating for depletion through production.

Price increases and improvements in extraction allowed a reduction in the average grade of copper ore mined from approximately 0.9 percent in 1950 to 0.7 percent copper per ton in 1966. This reduction in grade converted increasingly larger tonnages of lower-grade rock into ore, enabling total copper reserves to be increased. At least 16 new, large, disseminated copper deposits have been discovered since 1950. Eight of these are now in production. The addition to reserves from these new deposits alone has been substantial, without including the additions to reserves made by development at previously existing operations.

The *Paley Report* estimated in 1952 that domestic copper consumption would increase from 1.7 million tons in 1950 to 2.5 million tons (including scrap) in 1975.[155] This estimate was based upon prospective demand and on foreseeable changes in the use of copper for various products. No allowance was made, nor could there be, for unforeseeable new uses of copper. Aluminum was expected to substitute (and has) increasingly for copper in many metal products, particularly in electrical power transmission lines.

The view held by the Paley Commission was that mines operating and being developed in 1950 were producing (or would produce) at the most efficient and economic scale for the ore deposits concerned. Little if any additions to capacity were thought to be economically feasible at existing deposits. All known disseminated deposits made commercial by mass mining methods were then thought to be in production or in the process of development at optimum capacity. The copper industry was considered to have already exploited fairly exhaustively advances in technology to date. Virtually all of the remaining store of known occurrences of copper mineralization were considered to have been explored during and after World War II, and it was felt that those that were commercial had been or were being placed into production.[156]

The report concluded that additional copper to satisfy projected increases in demand would have to come largely from foreign sources, particularly in the event of war. Canada and Mexico could not supply all of any major war's import requirements. Furthermore,

Table 12

ESTIMATES OF COPPER RESERVES IN THE UNITED STATES

Year	Source		Reserves (millions of short tons)
1950	(Paley)	25.0	(*measured, indicated,* and *inferred*) Average grade of 0.9 percent copper
1955	(MF&P)	25.0	(*measured* and *indicated*)
1958	(Min. World)	50.0	(*measured* and *indicated;* 100 *inferred* are included)
1961	(Netschert)	32.5	(mostly *measured*)
1962	(Min. Res.)	32.5	
1963	(Landsberg)	40-50	(*measured* and *indicated*)
1964	(I.C. 8325)	41.99	(*measured* and *indicated;* 24.51 *measured*)
1964	(I.C. 8325)	85.99	(*measured, indicated,* and *inferred*)
1965	(CDS)	32.5	(Average grade of 0.8 percent copper)
1965	(MF&P)	32.5	(*measured* and *indicated*)
1967	(CDS)	33.0	(Average grade of 0.8 percent copper)
1968	(CDS)	85.5	(Average grade of 0.8 percent copper)

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Min. World = *Mining World*
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
I.C. = U.S. Bureau of Mines Information Circular

according to the report, there was not "much chance that further technological progress in mining would increase reserves significantly by making lower-grade deposits profitable, through lowering the minimum ore cut-off grade of available ore."[157] In addition the report assumed that the existing loss in beneficiation was an irreducible minimum of from one to two pounds of copper per ton of ore.

In 1950 the cut-off grade at most copper properties was roughly 0.5 percent, or 10 pounds of copper per ton of ore. The grade of ore is rarely uniform throughout a mineral deposit, and consequently, a break-even, or cut-off, grade is calculated. All rock assaying below cut-off grade is normally sent to the waste dump, and rock assaying higher than this grade is sent to the mill or smelter. The average grade of an orebody is generally higher than the cut-off grade, for otherwise there would be no profit.

Small changes in mineral commodity prices will affect the cut-off grade at a particular deposit by as much as 15 to 30 percent. If prices rise, the cut-off grade may be lowered, provided that labor and material costs have not also risen in proportion. Lowering economic grade, of course, increases the tonnage in the deposit, but the average amount of ore mineral extracted per ton of rock decreases. Ten to 25 percent of the ore mineral is usually lost in beneficiation and smelting, so that the effective ore recoverable grade used in cost and profit calculations is less than the actual grade of the rock.

The *Paley Report* has been criticized by many for its inaccuracies in the projection of supply and demand. Perhaps its greatest failing was that it did not project the ability of the mining industry to find new ore and develop cheaper methods of extracting copper from

Fig. 76 - The Bluebird copper deposit near Miami, Arizona. Long considered too low in copper content and mineralogically unsuited for existing methods of copper extraction, the Bluebird deposit remained waste until changing technology and economic conditions turned it into ore and increased the nation's known copper ore reserves.

lower-grade rock. It is interesting, however, to note that, subsequent to publication of the *Paley Report,* exploration for new copper deposits to satisfy projected increases in demand and to offset the expected depletion of reserves began to intensify, and has increased rapidly since. Seven new disseminated copper deposits have been discovered (Pima, Mission, Esperanza, Sierrita, Mineral Park, Berkeley Pit, Bluebird, and Battle Mountain) and put into production since 1952. These do not include the Copper Cities, San Manuel, Silver Bell, and Yerington deposits which were being developed at the time and which subsequently came into production. In the face of continually decreasing grades of ore (which the *Paley Report* recognized and predicted), both new and existing copper mines installed or expanded leach facilities to extract copper from what was otherwise rock of too low a grade to be processed in the normal manner, i.e., waste. The development of new machinery enabled more economic mining of lower-grade rock in larger volumes, thus maintaining operations and increasing copper production.

Prior to 1961 copper consumption remained more or less on an even keel, as the substitution of aluminum and other commodities made increasing inroads into copper markets. If this trend had continued, copper consumption in 1975 would not have been greatly different than that projected by the *Paley Report.* Copper consumption and production both accelerated from 1961 to 1968, however, coincident with the escalation of the Viet Nam War. These factors (which probably could not have been predicted), together with increased prices, hastened the adoption of more advanced leaching methods and more efficient machinery to extract ore. In 1966, mine production of domestic copper was 1.4 million tons and consumption (excluding scrap) was 2.2 million tons. The curve of increasing consumption, including scrap copper, reached 2.8 million tons of copper in 1966, nine years in advance of the *Paley Report's* 1975 target date.

The Paley Commission foresaw correctly the widening gaps between domestic production and wartime needs which has increasingly made the United States dependent upon foreign supplies of copper. Excluding scrap, 36 percent of domestic consumption was supplied by foreign sources in 1966, up from 18 percent in 1961.

Copper reserves have also been subject to varying estimates since 1950. In 1955, *Mineral Facts and Problems* estimated that the nation's reserves of copper in *measured* and *indicated* ore were about 25 million tons. By 1958, *Mining World* estimated that *measured* and *indicated* reserves of copper metal had increased to 50 million tons, and if *inferred* reserves were included, that the total would be 100 million tons. In 1961, Netschert and Landsberg in *The Future Supply of the Major Metals,* done for Resources for the Future, Inc., estimated that the nation's reserves of copper in *measured* ore totaled about 32 million tons. In 1963, Landsberg, writing in *Natural Resources for United States Growth,* published by the Johns Hopkins Press, indicated that *measured* and *indicated* domestic reserves of copper were between 40 and 50 million tons. The following year, the United States Bureau of Mines in its *Information Circular, 8325* estimated that the nation's *measured* and *indicated* reserves of copper amounted to nearly 42 million tons, 25 million tons of which were in *measured* ore. If *inferred* ore reserves were included, the estimate rose to nearly 86 million tons. By 1965 the Bureau of Mines' *Commodity Data Summaries* were providing an estimate of over 32 million tons of copper in ore with an 0.8 percent average grade, but by 1968 this had increased to over 85 million tons in ore of the same grade.

These other estimates of future production, consumption, and reserves have acknowledged the possibility of new ore discoveries and the treatment of lower-grade ore. The reserve estimates vary according to the assumed grade and proportions of *indicated* and *inferred* ore which may be deduced. Landsberg *et al.*[158] and Netschert and Landsberg[159] have estimated average annual copper production of 1.0 to 1.5 million tons through the year 2000, and Landsberg *et al:* estimated a 1985 consumption range of 2.4 to 7.6 million tons with a median estimate of 4.2 million tons of copper.[160] The trends in production since 1947, plus expansions of existing operations, the development of new mines, and the anticipated discovery of new deposits, suggest that 1985 copper production may rise to between 1.7 and 2.0 million tons per year. On the other hand, if the 1961-1966 trend continues, production could rise to a range of 2.4 to 2.8 million tons a year, or even more. Previous estimates (Landsberg, Netscher) did not take into account the full impact of the intensified efforts of recent years in minerals exploration and in extractive metallurgy which have substantially increased the nation's ore reserves and production capability.

The Landsberg *et al.* projections of consumption for 1985 include a substantial range, adequate to account for a variety of possibilities from heavy substitution of other metals for copper to tremendous expansion of copper usage. Projected estimates stated herein range from about 2.0 to 5.0 million tons of annual copper consumption in 1985, assuming that the most recent (1965-1966) acceleration in demand due to the Viet Nam War does not continue at its present rate of increase. A median consumption range of 2.5 to 3.5 million tons of copper in 1985 is projected assuming a certain, but not excessive, increase in the use of copper substitutes and barring a drastic acceleration of consumption due to political or technological factors.

Latest total estimated copper reserves (*Commodity Data Summaries,* January 1968, at 85.5 million tons) would be sufficient for more than 20 years of consumption at a 1985 rate of 3.5 million tons per year. *Measured* reserves, however, are only about one-third as large. In terms of operating capacity, therefore, useful copper reserves are not excessive, as evidenced by the strain on producing facilities caused by recent demand due to the Viet Nam War.

The *Paley Report* seems to have been equally as inaccurate in estimating the country's reserves of lead as in stating copper reserves. In 1950, the *Paley Report* estimated that the United States had, in *measured, indicated,* and *inferred* ore reserves, about seven million tons of lead. From 1951 to 1967, domestic lead mines, lead-zinc mines, and lead-silver mines had produced more than five million tons of lead and yet, according to the Bureau of Mines' *Commodity Data Summaries, measured* and *indicated* reserves of lead had increased to eight million tons. Furthermore, of the seven million tons of reserve estimated in 1950, only one million tons were considered to be in *measured* ore with the remainder being in *indicated* and *inferred.* The eight million ton estimate by the Bureau of Mines in 1967 did not include *inferred* reserves but only *measured* and *indicated.* By 1968, the Bureau of Mines estimate for domestic lead reserves had increased to a total of 35 million tons. A major portion of the reserves added in the most recent years has come from the new Viburnum district in Southeast Missouri where mineral deposits completely unknown only 10 years ago have been developed.

Most lead mines (including lead-zinc, lead-silver, and lead-zinc-silver) have consisted of a series of separate orebodies, requiring continuing exploration to maintain reserves ahead of mining. The grade of rock constituting lead ore, because of the relatively low unit price of lead, is more sensitive to small absolute price changes than many of the other metals. Consequently, net reserves have fluctuated as much with price changes as they have with the ratio of new mineral discoveries to depletion by mining. The increases in the prices of silver, zinc, and lead since the early 1960's have enabled progressively lower-grade deposits to become ore and thus be added to ore reserves.

The combination of continued successful exploration and price increases has resulted not only in the replenishment of mined out reserves but an increase in reserves. More important than exploration at and in the vicinity of existing operations, however, have been the discoveries of vast new lead deposits in Southeastern Missouri since 1960. These new Missouri deposits account for the major portion of the increase in net reserves since the 1950 Paley estimate.

Lead production followed a declining trend from 1947 to 1962, but has since increased following the discovery of the new Southeastern Missouri ore deposits. Lead output should continue to increase as new mines are put into production on these deposits, provided that excessive reductions in the metal's price are not experienced. The difference between domestic lead production and demand has been compensated for by imports (31 percent of consumption in 1966) and recovered scrap lead (40 percent of 1966 consumption). Currently estimated lead reserves of 35 million tons in *measured* and *indicated* ores are sufficient to supply demand for 30 years at the 1985 rate of projected consumption.[161]

Table 13

ESTIMATES OF LEAD RESERVES IN THE UNITED STATES

Year	Source	Reserves (millions of short tons)	
1950	(Paley)	7.1	(*measured, indicated,* and *inferred*)
1950	(Paley)	1.0	(*measured*)
1950	(Mat. Surv.)	2.9	(*measured* and *indicated*)
1951	(MF&P)	2.5	
1958	(Min. World)	2.9	(*measured* and *indicated*)
1960	(MF&P)	5.6	(*measured, indicated,* and *inferred*)
1960	(MF&P)	2.9	(*measured* and *indicated*)
1962	(Min. Res.)	7.7	
1962	(Mat. Surv.)	4.66	(*measured* and *indicated*)
1964	(I.C. 8325)	0.67	(*measured*)
1964	(I.C. 8325)	35.25	(*indicated* and *inferred*)
1964	(I.C. 8325)	16.15	(*measured* and *indicated;* includes all base metal ores)
1965	(MF&P)	6.0	
1967	(CDS)	8.0	(*measured* and *indicated*)
1968	(CDS)	35.0	

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Mat. Surv. = *Materials Survey,* U.S. Bureau of Mines
Min. World = *Mining World*
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
I.C. = U.S. Bureau of Mines Information Circular

In 1950, the President's Materials Policy Commission estimated that the United States had approximately 16 million tons of zinc in ore reserves. Approximately half of this was in *measured* and *indicated* reserves. Only a year before that, in 1949, the materials survey made by the U.S. Bureau of Mines had estimated the nation's reserves of zinc at 8.5 million tons in *measured* and *indicated* ore. In the same year as the *Paley Report* (1950), *Minerals Facts and Problems* estimated the nation had 8.5 million tons of *measured* and *indicated* zinc of which 6.5 million tons were *recoverable.* With *inferred* ore included, the estimate rose to 21 million tons, of which 16 million tons were *recoverable.* From 1951 to 1967, the nation's mines produced over nine million tons of zinc, and yet, in 1967, the *Commodity Data Summaries* of the Bureau of Mines indicated that the nation still had *measured* and *indicated* reserves of 12 million tons of zinc.

Reserves of zinc, like those of lead, have fluctuated according to the prices paid for lead, zinc, and silver, and with the success of exploration activities in active deposits. Discoveries of new zinc ore deposits have also been made. The net result of price increases and new discoveries has been that *measured* and *indicated* reserves have almost doubled since 1950, from 8.5 to 15 million tons of metal, despite the production in the meantime of over nine million tons of zinc.

Zinc consumption leveled off through 1960, then rose again, this time steadily, to 1966. The overall trend is in line with the Paley estimate of 1975 consumption. Assuming that the periods of depressed and accelerated consumption rates average out, the projected 1985 consumption of approximately 1.7 to 2.1 million tons of zinc is more or less in accord with the trend indicated by the *Paley Report* and with the median Resources for the Future projections. The Resources for the Future projections include high and low consumption estimates as well, which adequately cover the range from depression to wartime conditions.

Domestic zinc production has not been sufficient to satisfy the nation's demand, and since 1958 has amounted to half or less of total consumption. Competition from foreign imports has apparently restrained domestic production. Furthermore, the production of zinc and the production of lead are frequently interdependent, so that the reserve of one or the other metal is only partly responsive to its own demand. Lack of sufficient demand for lead has often inhibited the production of zinc, and vice versa.

Current *measured* and *indicated* reserves of zinc of 15 million tons are sufficient for ten years' consumption *at present rates.*[162] The development of *inferred* reserves should increase this figure to 20 years, or through 1985. Estimated potential reserves constitute twice the amount of total reserves, and may become ore at some time in the future depending upon the price situation and other factors. Future production is not likely to increase greatly, however, unless new, cheaply mineable orebodies are found or prices rise much higher. Newly discovered deposits in Tennessee may be such orebodies.

Both lead and zinc reserve estimates have been even more variable than iron or copper ore reserve estimates because of variations in the inclusion of by- and co-product ores and by distinctions between *measured, indicated,* and *inferred* reserves. In 1960 *Mineral Facts and Problems* estimated the nation's reserves of lead at 5.6 million tons in *measured, indicated,* and *inferred* ore, less than three million tons of which was in *measured* and *indicated* ore. By 1962, material surveys of the Bureau of Mines estimated the *measured* and *indicated* lead to total 4.7 million tons. By 1964, the Bureau of Mines *Information Circular 8325* stated the nation's *measured* lead reserves at 0.7 million tons. If *indicated* and *inferred* reserves were included, however, the estimate soared to 35 million tons. If only *measured* and *indicated* reserves were considered, and if the lead contained in all base metal ores (including those of copper, zinc, gold, and silver), then the total lead reserve was set at about 16 million tons of metal. By 1967 *measured* and *indicated* reserves were set at eight million tons.

Zinc reserve estimates have followed a similar pattern. In 1957, Netschert estimated the zinc contained in *measured* and *indicated* ores in the United States to be about 13.5 million tons, with the total involved in *measured, indicated,* and *inferred* reserves at 25 million tons. In 1964, *Information Circular No. 8325* estimated the nation's reserves of *measured* and

Table 14

ESTIMATES OF ZINC RESERVES IN THE UNITED STATES

Date	Source	Reserves (millions of short tons)	
1949	(Mat. Surv.)	8.5	(*measured* and *indicated*)
1950	(Paley)	16.0	(approximately 50 percent *measured* and *indicated; recovera*
1950	(MF&P)	8.48	(*measured* and *indicated*)
		6.53	(*recoverable*)
1950	(MF&P)	21.2	(*measured, indicated,* and *inferred*)
		16.3	(*recoverable*)
1957	(Netschert)	13.485	(*measured* and *indicated*)
1957	(Netschert)	25.0	(*measured, indicated,* and *inferred*)
		19.25	(*recoverable*)
1957	(Min. World)	25.0	
1962	(Min. Res.)	25.0	
1962	(MF&P)	12.2	(*measured* and *indicated*)
1964	(I.C. 8325)	15.07	(*measured* and *indicated*)
1964	(I.C. 8325)	28.67	(*measured, indicated,* and *inferred*)
1965	(CDS)	12.0	(*measured* and *indicated*)
1967	(CDS)	12.0	(*measured* and *indicated*)
1968	(CDS)	15.0	(*measured* and *indicated*)

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Mat. Surv. = *Materials Survey,* U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Min. World = *Mining World*
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
I.C. = U.S. Bureau of Mines Information Circular

indicated zinc at about 15 million tons, with the inclusion of the *inferred* reserves sending the total up to nearly 29 million tons. Estimates since that time have varied between 12 and 15 million tons.

2. Reserve Estimates for Minor Metals

Estimates of mercury ore reserves in the United States have been extremely variable, with the status of reserves highly questionable depending upon the current price or short term future expected price of mercury. The price of mercury itself has fluctuated greatly since the end of World War II. In 1950, the Paley Commission estimated that the nation had nearly 400,000 flasks of mercury in ore containing ten pounds per ton or more of mercury and nearly 600,000 flasks of mercury in ore containing five pounds per ton or more. By 1967, more than 500,000 flasks of mercury had been produced and yet the nation's reserves of mercury were still substantial.

Price fluctuations, more than anything else, have controlled the nation's reserves and production of mercury since 1950. Stimulated by higher prices, new ore discoveries, mostly at previously operated or operating deposits have been made and added to known mercury reserves. On the other hand, increasing costs of production have tended to decrease mineable reserves so that even with the substantial price increase from about $81 in 1950, to over $200 per flask in the 1952-1963 period, the average grade of ore mined generally remained at between seven and ten pounds per ton. Reserves, therefore, have not benefited by the price increases as much as would have been presumed, i.e., the average grade of ore did not drop to three pounds per ton as a similar price increase would have done with many other metals.

Despite the domestic production of nearly 400,000 flasks of mercury since the Paley estimate, new ore discoveries and price increases have raised 1968 estimated reserves to over 800,000 flasks. Most of these reserves are in the *inferred* and *resource* category, however. The scattered and discontinuous nature of mercury deposits, coupled with minimum exploration ahead of mining, has kept *measured* and *indicated* reserves small. The 1962 estimate, for example, is a projection of the grade of rock which would become ore at a given price coupled with estimates of how much rock of that grade might be available or readily found. These estimates are not accurate measurements of rock of different grades known to be present in different deposits, because such calculations on reserve are rarely made or kept by individual operators or owners.

The *Paley Report* estimated 1975 consumption in the United States at 60 to 65 thousand flasks of mercury, not counting for the possible development of new technological uses.[163] Annual domestic production was considered unlikely to rise much above 10,000 flasks due to the occurrence of mercury in scattered small deposits, the average economic grade of approximately 10 pounds of mercury per ton of ore (in 1950), and foreign control of the price (and consequently production) of mercury. The gap between domestic mercury production and consumption has been filled by imports, and in recent years, by releases from the Atomic Energy Commission and GSA stockpiles.

Most of the country's imported mercury, and most free world production, comes from producers in Spain and Italy. Spanish mercury production and marketing is under Spanish government control. Producers in those two countries have operated in the past under a cartel arrangement, resulting in world control of mercury prices and production. Spanish and Italian ore reserves are considerably higher, both in tonnage and grade, than are United States ore reserves. The mercury reserves of Spain and Italy were estimated at 1.75 million flasks of 20 to 60 pound ore in 1950. This represented only a portion of the potential since, "only a part of the known foreign mineralized areas have been explored, and it is expected that enough new ore (of grade comparable to that now being mined or richer than in the larger United States mines) will be discovered to extend known reserves two to five times."[164]

The impact of foreign activities upon domestic mineral reserves has been demonstrated quite forcefully with respect to mercury. As the Paley Commission noted,

Table 15

ESTIMATES OF MERCURY RESERVES IN THE UNITED STATES

Date	Source		Reserves (thousand flasks)
1950	(Paley)	395	(grade of 10 lbs/ton or greater)
1950	(Paley)	595	(grade of 5 lbs/ton or greater)
1952	(MF&P)	595	(grade of 5 lbs/ton or greater)
1957	(MF&P)	315	($250/flask)
1957	(MF&P)	575	(grade of 5 lbs/ton or greater and $400/flask)
1961	(Min. Res.)	300	
1961	(MF&P)	379	($300/flask)
1961	(MF&P)	827	($500/flask)
1961	(MF&P)	1.287	($1000/flask)
1962	(I.C. 8252)	76	($190/flask)
1962	(I.C. 8252)	228.5	($250/flask)
1962	(I.C. 8252)	100	($200/flask)
1962	(I.C. 8252)	280	($300/flask)
1962	(I.C. 8252)	500	($500/flask)
1962	(I.C. 8252)	1,000	($760/flask)
1967	(CDS)	75	
1968	(CDS)	825	

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S: Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
I.C. - U.S. Bureau of Mines Information Circular

> "Fluctuations by operations of the Spanish-Italian mercury cartel . . . at times maintained prices at levels that stimulated United States output, while at other times it threw large inventories on the market so that prices were depressed and United States output discouraged. . . . although the cartel was reportedly dissolved in 1950, the concentration of supply would permit its reestablishment at any time."

Increases in the price of mercury after 1950 stimulated production well above the *Paley Report's* estimated average annual rate of 10,000 flasks. Had the Spanish and Italian interests chosen to increase their sales of mercury in keeping with past practices, they could have held the price down and domestic production would have remained more in line with the Paley estimate.

The consumption of mercury through 1961 maintained a rising trend which would have projected close to the 1975 Paley estimate. The arms and space races, however, along with the Viet Nam War and a large expansion in the number and size of caustic soda plants (which require large initial amounts of mercury to start production), contributed to a demand for mercury in excess of the Paley estimate for 1975.

The effect of price upon the grade of ore and the ore reserves which are available are illustrated in Figure 78, which shows the relationship between price and ore available or easily explored for at that price. In 1951 the price of mercury rose from less than $100 to more than $200 per flask, and production began rising. This price increase also spurred exploration and development, but peak production did not occur until 1958, seven years later, reflecting the time required to expand existing mines, find new ore, and put new mines into operation. Production subsequently fell almost steadily until 1964, as rock constituting ore at approximately $200 per flask was exhausted and mines were shut down. The price of mercury began rising again in 1964, but production did not respond until 1965. Production leveled off in 1966 and 1967, because of reduced operations at the Cordero, Nevada, mine (resulting from fire damage) and the absence of readily accessible ore even at $400 plus per flask.

There are currently less than a dozen mercury mines of any consequence in the United States, and their reserves are being exhausted at an increasing rate. In order for production to increase or maintain its current rate, new mines and orebodies will have be found and brought into operation. Provided that the current price of mercury is maintained or increased, exploration activity now in progress will probably bring in some new small mines. The greatest hope for any sustained major increase in production lies in the discovery and development of large low-grade orebodies amenable to high-volume, low-cost mining methods. Orebodies of this type will probably be found and brought into production within a few years if the present price for mercury remains steady or increases. Portions of Nevada, California, and Texas are known to possess the potential for large low-grade mercury deposits. Most mining companies, however, have hesitated to consider projects requiring the major expenditures typical of large low-grade mineral deposits for fear that increased foreign production and lower prices would not permit recovery of their investment.

Projection of the production trend since 1947 indicates a 1985 production range of from 18,000 to 55,000 flasks of mercury per year, with a median of 41,500 flasks annually. If large, low-grade deposits are brought into production, domestic production could rise to a range of 70,000 to 90,000 flasks or even higher by 1985. These estimates depend, of course, upon non-adverse price changes caused by the actions of foreign producers.

Demand for mercury is expected to continue to grow, either at the slower 1947-1967 rate or the accelerated rate of the past six years. Foreign policy and the state of the nation's economy will to a large degree dictate the rate of growth in mercury consumption. The projected median range of consumption in 1985 is approximately 120,000 flasks.

A number of the metals commonly used in steel alloys have also been the subjects of highly variable ore reserve estimates. In 1950, the Paley Commission estimated that the

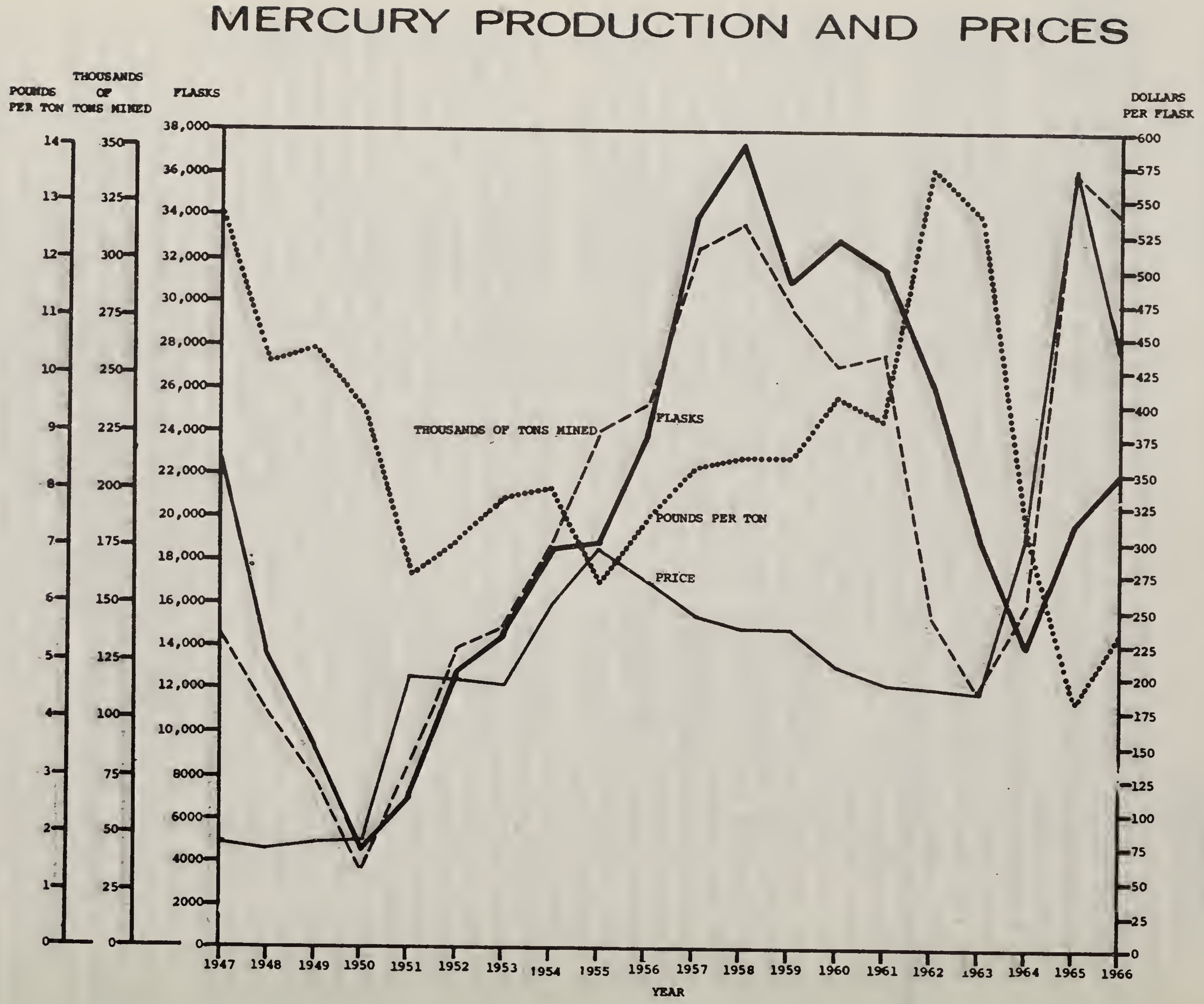


Fig. 77 - Changing domestic mercury production and prices. For many mineral commodities, ore reserves are easily and immediately decreased by falling prices or rising costs, but increases in ore reserves often involve substantial time lags as new deposits must first be found before they can be measured and evaluated.

United States had only half a million tons of nickel reserves. In the period from 1951 to 1967, the nation produced nearly 200,000 tons of nickel. Most of this took place after 1954 when the Riddle, Oregon, deposit of the Hanna Mining Company was brought into production. Despite an initial reserve (in 1950) of half a million tons, and production since then of 0.2 of a million tons, *Commodity Data Summaries* in 1968 estimated one million tons of domestic nickel reserves including *measured, indicated,* and *inferred* reserves.

Domestic nickel reserves have varied according to the nickel content of the rock included in the estimate. Negligible amounts of nickel were mined in the United States until the Riddle, Oregon, deposit began operating in 1954. Since then, approximately 170,000 tons of nickel have been mined at Riddle. Reserves were maintained more or less constant, however, through the development of sufficient additional ore to replace production until 1968. The inclusion of lower-grade rock in the estimated reserves in 1968 contributed to a doubling of the reserve estimate from about 0.5 to 1.0 million tons of nickel.

More than a fourth of the nation's present nickel reserves are contained in nickeliferous iron ores as by-product metal, and in sulfide ores from which there has been little production. Most of the domestic nickel consumption has been supplied by imports, of which about 90 percent have come from Canada in recent years.

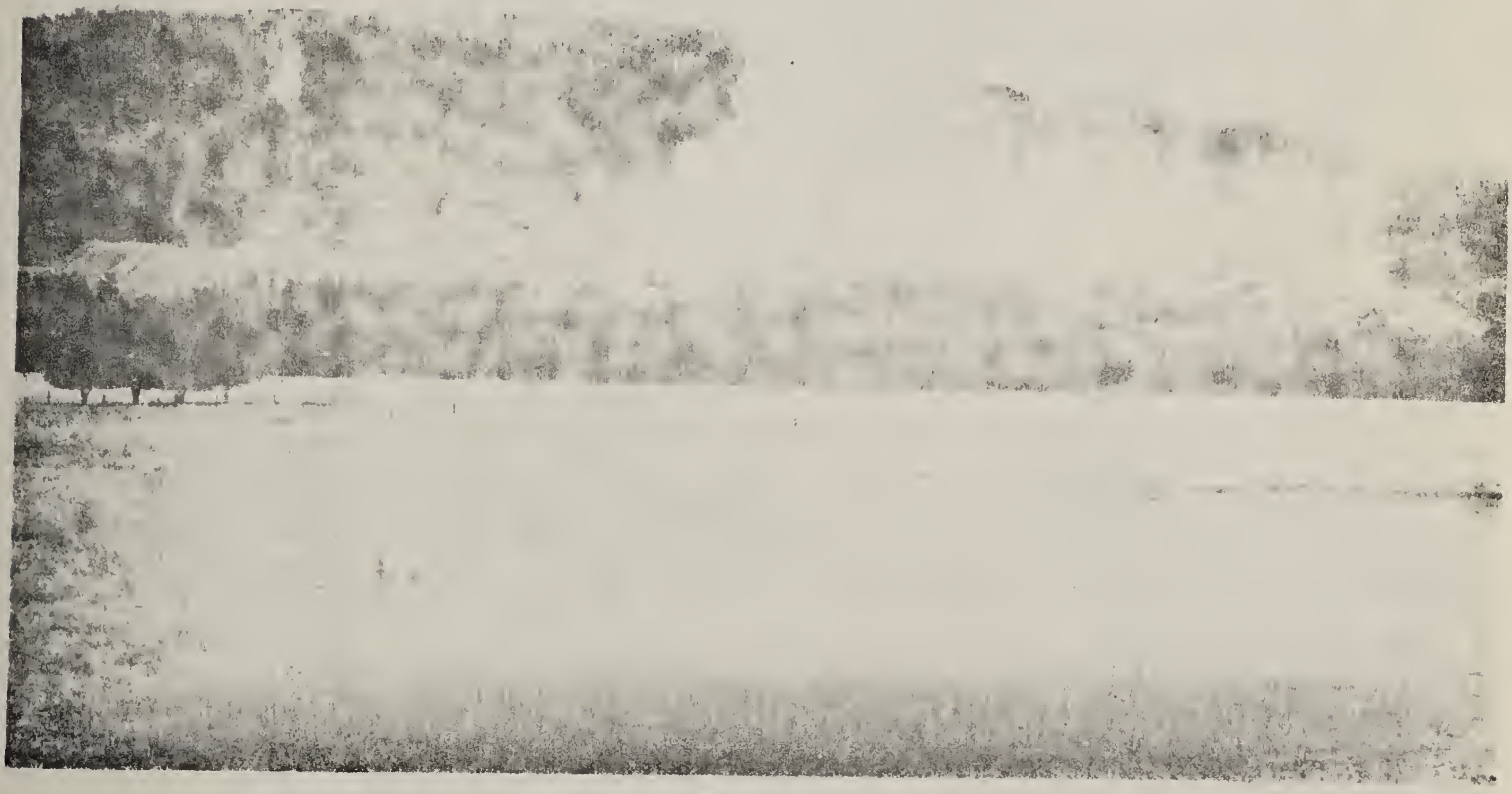


Fig. 78 - The nation's only significant known nickel deposit. Undeveloped at the time of the Paley Report in 1950, this deposit near Riddle, Oregon, has since been responsible for substantially increasing the nation's known nickel reserves.

Table 16

ESTIMATES OF NICKEL RESERVES IN THE UNITED STATES

Date	Source	Reserves (millions of short tons)	
1950	(Paley)	0.5	
1962	(Min. Res.)	0.4	
1964	(MF&P)	0.5	(0.36 million tons in silicates, 0.14 million tons in sulfides)
1950	(Mat. Surv.)	0.54	(0.14 million tons in sulfide in Alaska and the 48 contiguous United States; 0.4 million tons in silicates and nickel in ores of other metals)
1965	(CDS)	0.5	(0.7 percent nickel)
1967	(CDS)	0.243	(1.5 percent nickel, approximately equivalent to 0.5 million tons in 0.7 percent ore)
1968	(CDS)	1.0	(0.4-1.5, *measured, indicated,* and *inferred*)

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
Mat. Surv. = *Materials Survey,* U.S. Bureau of Mines

Nickel consumption trends from 1947 to 1964, projected to 1985, fall short of the *Paley Report* estimate of 200,000 tons of United States nickel consumption in 1975. From 1964 to 1967, demand accelerated, however, due to war and space age requirements. If this recent trend continues, even with some leveling off, 1985 consumption could be in the range of 290,000 to 310,000 tons of nickel, and the *Paley* estimate for 1975 will fall far short of the mark. The 1947-1963 and the 1964-1967 trends represent two extremes in projected demand for 1985, from a low estimate of 150,000 to a high of 310,000 tons of nickel. War, depression, and substitutes for nickel or increased demand resulting from technological change represent opposing alternatives which could modify any projection of a "normal" increase in demand. An intermediate projection of 230,000 to 270,000 tons of nickel consumed in 1985 seems most likely, assuming that modifying factors will average out more on the plus side than the minus side of consumption.

Known domestic nickel reserves and current production are woefully inadequate to supply existing and expected domestic demand. Exploration for nickel in the United States is increasing, however, for both silicate and sulfide ores. Present information on exploration activity now in progress suggests the possibility of enough new nickel discoveries being made to increase production substantially. The United States will probably remain, however, largely dependent upon foreign supplies of nickel for a considerable time.

Contrary to nearly all other mineral commodities, the nation's tungsten reserves have decreased since the 1950 estimate by the *Paley Report*. But the decline has not been nearly as much as the production that has taken place since then. In 1950, the Paley Commission estimated that the United States had nearly 159 millions of pounds of tungsten metal existing as tungsten oxide in ore that included *measured, indicated,* and *inferred* ores containing at least 0.4 percent tungsten oxide. Between 1951 and 1966, more than 130 million pounds of tungsten were produced in the United States. Nevertheless, by 1967 the *Commodity Data Summaries* of the Bureau of Mines estimated that the nation still had 143 million pounds of tungsten in *measured, indicated,* and *inferred* ore reserves containing a minimum of 0.3 percent tungsten oxide.

A large portion of post-1950 tungsten production has been as a by-product from tungsten contained in what is essentially molybdenum ore at Climax, Colorado. In recent years, Climax has been the second largest single source of tungsten in the United States. Tungsten reserves and production have therefore been dependent to a great extent upon the maintenance of molybdenum reserves and the rate of molybdenum production at Climax.

High tungsten prices (from approximately $40.00 to $66.00 per short ton unit of tungsten oxide, WO_3, which is equivalent to 15.86 pounds of tungsten) during the early and middle 1950's resulted in the discovery and development of many small tungsten deposits in the Western United States. The high prices were maintained by the government for stockpile

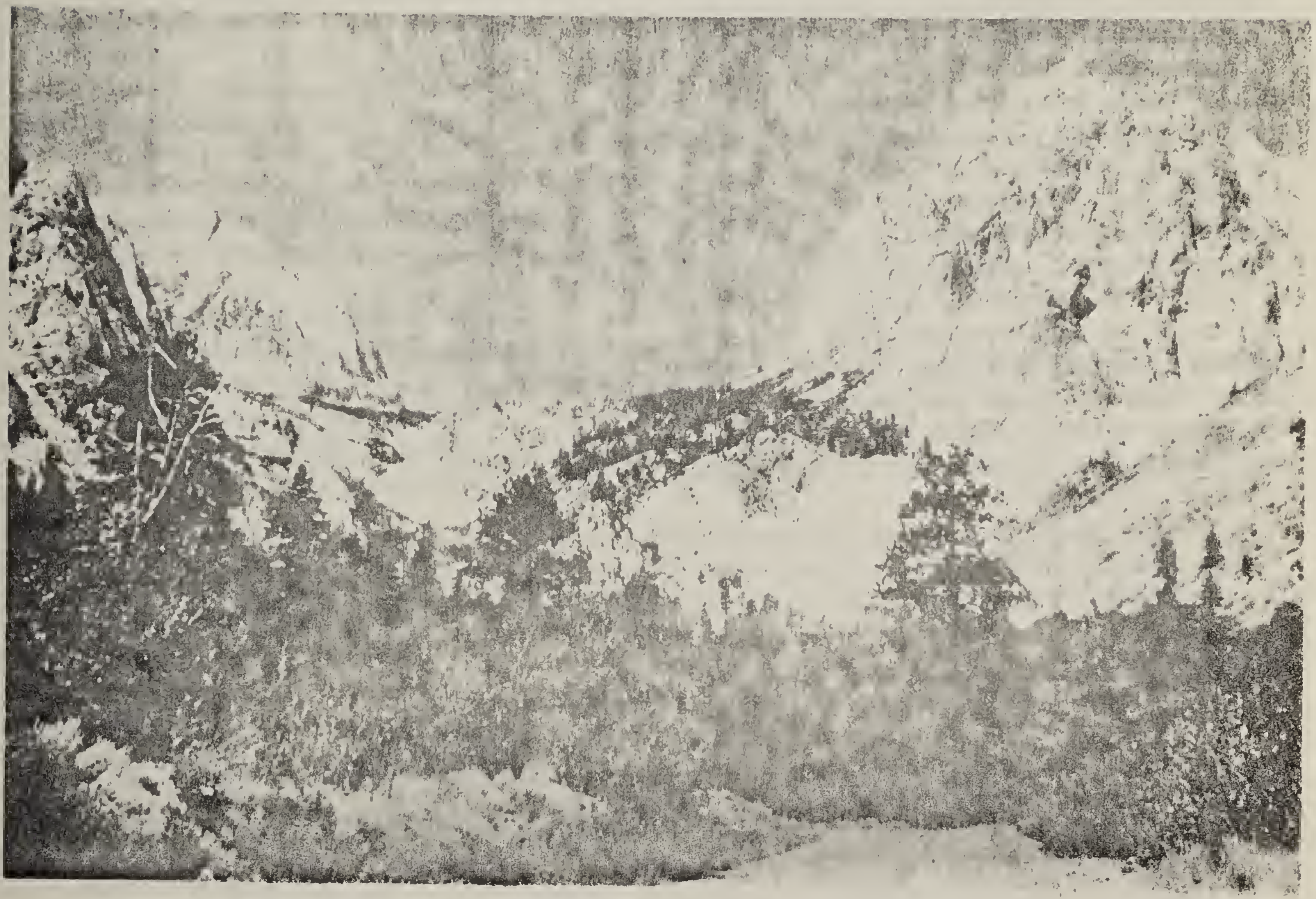


Fig. 79 - The tungsten mineral deposit near Bishop, California, one of the few domestic mineral deposits utilized primarily for its tungsten content. Although substantial reserves of by-product tungsten have been developed in the past 15 years, the nation's total known tungsten reserves have declined.

and Korean War demands. Subsequent purchase contracts were given preferentially to foreign sources of supply, however, and domestic prices fell below $20.00 per short ton unit.

This sharp decrease in price made most domestic tungsten operations unprofitable, causing nearly all of the nation's primary tungsten mines to shut down and a large portion of the nation's tungsten ore reserves to vanish.

Prices have improved since the late 1950's and a few mines are now operating again. Most of the nation's production now comes from Climax and two deposits in California, one of which depends upon other metal values besides tungsten for profitable operation.

Tungsten reserves at the grades given (0.3 to 0.4 percent tungsten oxide) really constitute only potential reserves, except during periods of high prices or as co- or by-products of other metals. The development of additional ore at producing properties and new discoveries during periods of high prices have maintained the level of reserves shown in Table 17 in the face of continued production. Variations in the estimates for different years are caused by individual assumptions as to the quantity of *inferred* ore, grade, and changes in the ratio of newly-discovered ore to production.

A considerable portion of estimated domestic tungsten reserves have been locked up in non-producing properties as unusable "resources" since the price drop of the late 1950's. Furthermore, a substantial portion of the currently estimated tungsten reserves are "inferred" reserves, and their utilization is contingent upon successful development under favorable conditions and high prices. Known useful reserves (those from which production is made) are not more than about half as large as total reserves, even at favorable prices. Reserves responsive to increases in demand (i.e., not contingent upon production as a co- or by-product of other ores) probably do not constitute more than 25 percent of total domestic tungsten reserves.

Since 1958 the nation's domestic mine production has supplied a steadily declining proportion of the domestic demand for tungsten. In 1966 domestic mines supplied less than half of domestic consumption. Total currently estimated tungsten reserves of 143 million pounds are insufficient to supply demand through 1985, even at the depressed 1964 rate of consumption. Responsive tungsten reserves are in even shorter supply. Barring adequate price increases and/or new ore discoveries, the United States could become almost totally dependent upon foreign sources for tungsten by 1985.

The 1950 estimate of beryllium ore reserves in the United States has been noticeably inaccurate. In that year the Paley Commission estimated that the United States had 15 thousand tons of beryllium ore. This existed primarily as beryl in pegmatites. Since that time, however, large low-grade deposits of minerals containing beryllium have been discovered in Utah, and by 1967 the *Commodity Data Summaries* of the Bureau of Mines were led to state simply that known reserves of beryllium ore in the United States were "large and low-grade."

In 1964, however, a report on the mineral and water resources of Utah by the U.S. Bureau of Mines estimated the nation's beryllium reserves at 15 million tons (compared to the 15 thousand tons in the 1950 Paley estimate) containing at least 0.5 percent beryllium oxide. This would be equivalent to 600 thousand tons of beryl, the ore mineral involved in the 1950 estimate.

Beryllium normally occurs in three major types of deposits: pegmatites (in which beryl is the ore mineral), veins, and disseminated (in volcanic rocks), in which other beryllium-bearing minerals constitute the ore. Known disseminated and vein ore deposits in Utah contain large reserves of beryllium, but have not as yet had any production due in large part to technical problems preventing profitable extraction.

The *Paley Report* estimated domestic reserves of approximately 15,000 tons of beryl from pegmatite sources, in which beryl is produced largely as a co- or by-product of mining for other minerals, chiefly feldspar and mica. The 1953 *Materials Survey* estimate was more specific, assigning tonnages to rock of different beryl content, and also included non-pegmatite sources of beryllium. Not quite 2,000 tons of beryl were mined in the United

Table 17

ESTIMATES OF TUNGSTEN RESERVES IN THE UNITED STATES

Date	Source	Reserves (millions of pounds of tungsten metal)	
1950	(Paley)	158.62	(*measured, indicated,* and *inferred* at + 0.4 percent tungsten oxide [WO_3])
1954	(MF&P)	142.76	(*measured, indicated,* and *inferred*)
1955	(MF&P)	154.34	(*measured, indicated,* and *inferred*)
1957	(Landsberg)	142.0	
1958	(Min. World)	142.76	
1962	(Min. Res.)	142.0	
1965	(CDS)	143.0	(2 0.3 percent WO_3)
1967	(CDS)	143.0	(*measured, indicated,* and *inferred*; at 0.3 percent WO_3)
1968	(CDS)	143.0	(at 0.3 percent WO_3)

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Paley = President's Materials Policy Commission (*Paley Report*)
Min. World = *Mining World*
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey

States between 1950 and 1953, and the discrepancy between the two estimates is a matter of the grade of beryl-bearing rock used in making the estimates.

From 1951 through 1962, almost 5,000 short tons of beryl were mined in the United States. The net reduction in reserve estimates between 1950 and 1962 was about 5,000 tons, largely reflecting depletion of ore through production.

Beryl is distributed unevenly in pegmatite deposits and the estimation of either reserves or resources is extremely difficult. Few on-the-ground measurements have been made of the actual grade and tonnage of reserves at individual properties, and domestic reserve estimates of beryl in pegmatites are perforce only educated guesses. The same has applied in the past to non-pegmatite resource estimates of beryllium ore.

Nevertheless, substantial additions to the nation's beryllium reserves have been made by the disseminated deposits in Utah which were discovered early in the 1960's. These deposits have been moderately to extensively sampled by drilling and surface and underground excavations. Consequently, reserve estimates for these deposits, which were not previously included in published reserve estimates, should be reasonably accurate. Although the disseminated and vein deposits in Utah are currently estimated to contain a minimum of 600,000 tons of beryl equivalent, these deposits have not been included in other reserve estimates.

Table 18

ESTIMATES OF BERYLLIUM RESERVES IN THE UNITED STATES

Date	Source	Reserves (short tons)	
1950	(Paley)	15,000	
1953	(Mat. Surv.)	11,000	(of + 1.0 percent beryl, in pegmatite)
1953	(Mat. Surv.)	270,000	(of + 0.1 percent beryl, in pegmatite)
1953	(Mat. Surv.)	3,000	(equivalent of + 0.1 percent BeO, nonpegmatite)
1953	(Mat. Surv.)	7,000	(equivalent of + 0.01 percent BeO, nonpegmatite)
1962	(Min. Res.)	10,000	
1964	(Min. & Water Res. Utah)	15,000,000	(0.5 percent BeO, minimum, equivalent to 600,000 tons of beryl)
1967	(CDS)	Large, low-grade resources	

Sources: MF&P = *Mineral Facts and Problems*, U.S. Bureau of Mines
CDS = *Commodity Data Summaries*, U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Mat. Surv. = *Materials Survey*, U.S. Bureau of Mines
Min. Res. = *Mineral Resources of the United States*, U.S. Geological Survey
Min. & Water Res. Utah = *Mineral and Water Resources of Utah*, Committee on Interior and Insular Affairs

Annual consumption of beryllium in the United States is projected to a 1985 range of from 11,000 to 15,000 tons. Once the large Utah deposits come into production, the increased availability of beryllium may cause an expansion of its use in a large number of products, and consumption could increase to several times the amount presently projected for 1985. The Utah deposits appear to contain sufficient beryllium to satisfy any such increases in demand through at least that year.

With so much of the nation's beryllium requirements coming from overseas, the reserve estimates for domestic beryllium supply have been quite variable. In 1953, estimates of domestic beryllium reserves ran as high as 270,000 tons of 0.1 percent beryllium oxide from pegmatites down to 3,000 tons equivalent to 0.1 percent beryllium oxide from non-pegmatite ores. Most recent estimates have simply stated that the nation's domestic beryllium reserves are "large."

Although the *Paley Report* made no mention of the nation's uranium reserves, a number of other estimates produced by the United States Bureau of Mines did. In 1940, it was estimated in *Mineral Facts and Problems* that the United States had about one million tons of uranium ore reserves of unstated grade. By 1950, according to the same source, this had increased to two million tons, likewise with the grade unstated. The 1968 *Annual Report of the United States Atomic Energy Commission* estimated that domestic reserves of uranium ore were approximately 64 million tons of about 0.23 percent U_3O_8. This huge increase came despite the fact that from 1948 to 1967 the nation produced more than 158,000 tons of uranium oxide. In other words, the total tonnage produced from 1948 to 1967 was more than twice the reserves estimated for 1968 and nearly 80 times as great as the reserve estimated in 1948.

Uranium ore reserves estimated since 1947 have increased from one million tons (containing probably less than 10,000 short tons of uranium oxide, U_3O_8) in 1948, to 64 million tons of 0.23 percent uranium oxide (containing 148,000 tons of uranium oxide) in 1968. The reserves were increased through the discovery of new mineral deposits and the development of new reserves at producing mines. Estimated reserves were highest in 1959 when they reached 241,000 tons of uranium oxide and subsequently fell to 152,000 tons of uranium oxide in 1965 because of depletion through production. About 5,000 tons of additional reserves were developed during this period, holding the net drop in reserves to 89,000 tons. Reserves were subsequently maintained more or less constant to 1968 through continued mine development and the resumption of outside exploration in anticipation of rising demand for uranium in the 1970's. Since early 1967 the tonnage of uranium oxide estimated to be in domestic ore reserves has climbed to nearly 200,000 tons according to the most recent *Commodity Data Summary.*

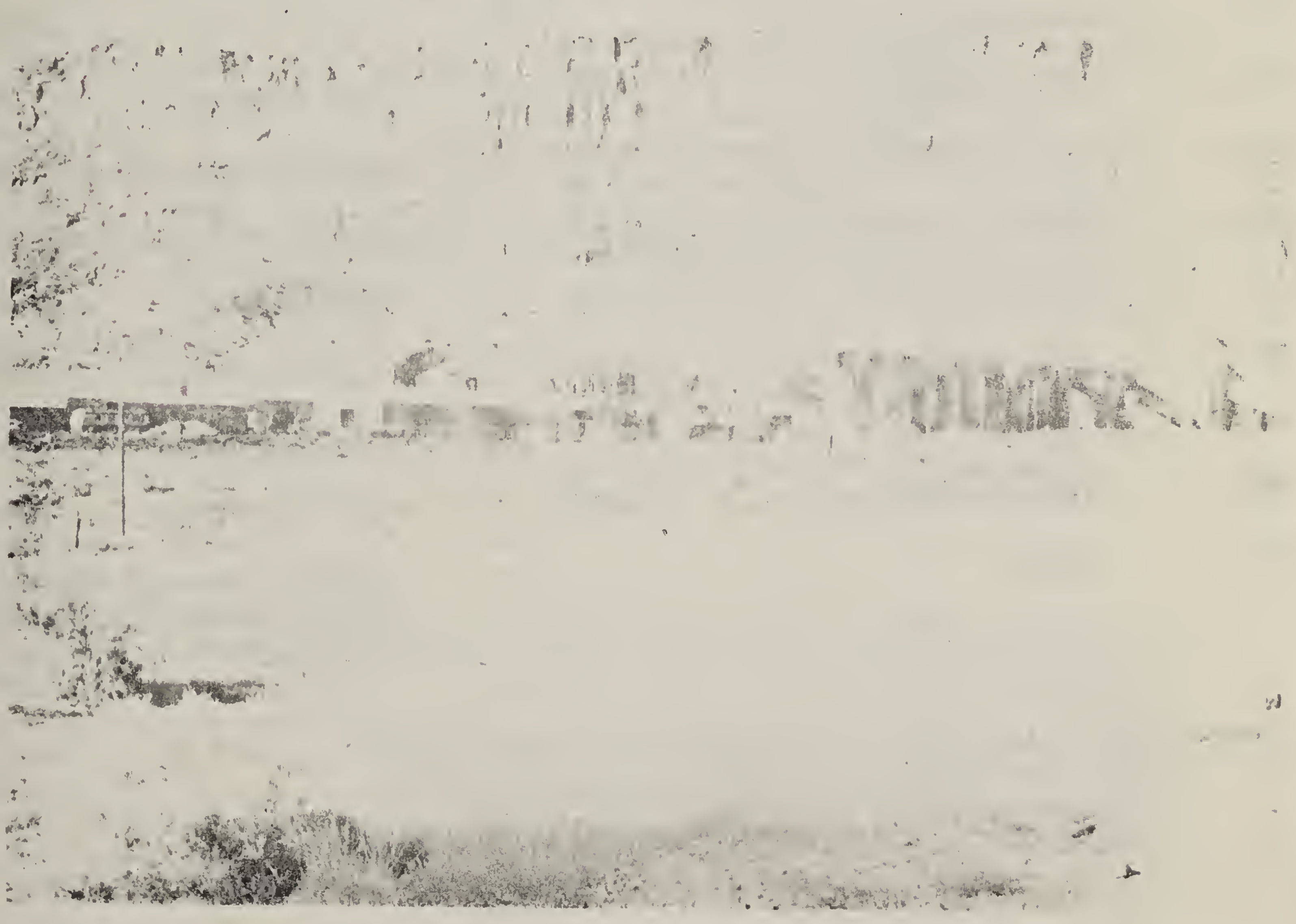


Fig. 80 - Concentrating facilities near Moab, Utah, built to process uranium ores from scattered deposits in the Colorado Plateau region of Southeastern Utah, Although estimated uranium reserves in 1968 were far greater than in 1947, there has been a decline from the peak years in the late 1950's.

Table 19

ESTIMATES OF URANIUM ORE RESERVES IN THE UNITED STATES

Date	Source	Reserves		
		(millions of tons) of ore		(tons of U_3O_8)
1948	(MF&P, 1965)	1		
1950	(MF&P, 1965)	2		
1955	(MF&P, 1965)	27		
1959	(MF&P, 1965)	88.9		
1959	(Jan. AEC Rept)	86.0	(at 0.28 percent U_3O_8)	241,000
1960	(MF&P, 1965)	82.0		
1963	(MF&P, 1965)	66.0		
1964	(Landsberg)			250,000
1965	(Jan. AEC Rept.)	63.0	(at 0.24 percent)	152,000
1966	(Jan. AEC Rept.)	61.0	(at 0.235 percent)	145,000
1966	(Dec. AEC Rept.)	63.0	(at 0.24 percent)	152,000
1967	(Jan. AEC Rept.)	61.0	(at 0.23 percent)	141,000
1967	(Dec. AEC Rept.)	64.0	(at 0.23 percent)	148,000
1967	(CDS)		(at 0.24 percent)	145,000
1968	(AEC Annual Rept.)	64.0	(at 0.23 percent)	148,000
1968	(CDS)	–	195,000 (*measured*, 325,000; *inferred*, 52,000, total, at $10.00/pound or less, of U_3O_8 content)	

Sources: MF&P = *Mineral Facts and Problems*, U.S. Bureau of Mines
CDS = *Commodity Data Summaries*, U.S. Bureau of Mines
AEC = Atomic Energy Commission

The Landsberg estimate of 1964 and contemporary AEC estimates of uranium oxide in ore reserves differ markedly (250,000 vs. 152,000 tons). This difference is probably accounted for by the amount of *inferred* reserves allotted to the respective estimates. The 1968 *Commodity Data Summaries'* reserve estimate of 195,000 tons of *measured* uranium oxide plus 325,000 tons of *inferred* was made at a price of $10 per pound of uranium oxide. As actual prices have been less than $10 per pound, this estimate obviously includes lower-grade rock than other estimates, thereby increasing the reserve tonnage figures. The AEC estimates apparently have not included *inferred* reserves.

Until recently the sale of uranium has been restricted almost exclusively to the Atomic Energy Commission. Production and consumption data therefore reflect purchases by the AEC, which in turn has sold uranium to qualified private consumers, principally for research and nuclear power plant fueling.

Domestic consumption (AEC domestic plus foreign procurement) and production both reached a peak in 1960. The satisfaction of immediate AEC demand led to the reduction of imports and "stretched out" domestic production contracts which steadily declined from 1960 to 1966. Production increased in 1967, exceeding consumption, in anticipation of projected demand for uranium to be used in nuclear power plants now being planned or constructed. Future demand is estimated (from data in the *Annual Report to the Congress of the AEC* for 1967) at around 25,000 tons of uranium oxide per year in 1975. The widespread use of breeder reactors, requiring less uranium, is not expected to occur until some time after 1980. Unit demand for uranium in breeder reactors may thus decrease at that time. Overall demand, however, may increase as the applications of nuclear power are better understood and come into more widespread use. Growth in uranium consumption from technological advancements has tended to feed upon itself, expanding at an increasing rate as more and more uses are developed. Consequently, uranium oxide consumption in 1985 is probable at between 30,000 and 40,000 tons per year, and could rise even further.

Total estimated reserves (1968 *Commodity Data Summaries* – 520,000 tons, including *inferred* reserves) of uranium oxide may be more or less sufficient to satisfy projected domestic needs through 1985, if *inferred* reserves are subsequently proven. Exploration currently underway should increase these reserves, particularly if lower-grade (less than 0.2 percent uranium oxide) rock becomes ore through price increases and/or technological improvements in extractive methods. Domestic production of uranium may be subjected to increasing competition from foreign sources of supply, however, chiefly in Africa and Canada, depending, of course, upon federal policy and relative prices and costs of production. According to demand and the severity of foreign competition, domestic production in 1985 may range from 20,000 to 30,000 tons of uranium oxide per year.

3. Precious Metals Reserves

Neither the *Paley* nor the *Resources for the Future* studies made estimates of reserves on future production and consumption of either silver or gold. The traditional association of these two metals with monetary policy has made predictions of consumption on technical or solely economic bases difficult and unreliable. Since the *Paley Report* in the early 1950's, however, various other sources have made estimates of reserves of the precious metals in the United States. Most of these estimates had similar discrepancies between total estimated reserves and subsequent production followed by later reserve estimates. In virtually all cases the reserve estimates appeared to be low.

In 1955, *Mineral Facts and Problems*, published by the United States Bureau of Mines, estimated that the nation had approximately 69 million troy ounces of *measured, indicated,* and *inferred* gold reserves. By 1968, according to the Bureau's *Commodity Data Summaries,* and despite the production between 1951 and 1967 of more than 29 million troy ounces of gold, the nation's *measured* and *indicated* reserves stood at 54 million ounces. The latter included by-product gold in primary copper reserves and in lead and zinc ores.

Estimates made of gold reserves over the years have varied widely. In 1955 the estimate was 69 million ounces in *measured, indicated,* and *inferred* ores. By 1964, according to the Bureau of Mines, the nation's gold ore reserves had dropped to 22 million ounces in *measured, indicated,* and *inferred* ore, including by-product gold in ores of other metals. From 1965 through 1967 the Bureau of Mines estimated reserves at 20 million troy ounces. By 1968, however, the estimate had climbed to 54 million ounces, undoubtedly because of the discovery and development of large low-grade gold deposits in Nevada.

Gold reserve estimates in the past have varied widely according to the relative proportions of *measured, indicated,* and *inferred* ore reserves which have been included in the estimates. Reserve figures have thus ranged from 20 million ounces (*measured* and *indicated*) to as much as 400 million ounces. Unfortunately the latter figure, as large and comforting as it may be, consists largely of potential reserves which are not of sufficient grade to be considered ore at present prices. It also includes non-responsive reserves of by-product gold from base metal ores. Only nine million ounces of gold, or about two percent of the total estimated reserve, are actually producible from primary ore at a price of $35 an ounce.[165]

Reserves of gold from primary gold ore declined steadily from 1947 to 1964, after which they were increased by the new discovery of the Carlin low-grade gold deposit in Nevada. Between 1947 and 1964, some gold ore was added to the nation's reserves, but depletion through mining was greater. Total reserves were maintained, however, through large additions of by-product gold from new base metal deposits. The increase in reserves from the 1964 to the 1968 estimates (*measured* plus *indicated*) reflects the addition of the Carlin and possibly the Cortez deposits plus new base metal developments.

The price of gold has been held by the government at a fixed price of $35 an ounce in the United States from the early 1930's to early 1968 as a monetary standard. Early in 1968, however, gold was released from its fixed price for commercial purposes and by mid-1968 had risen to approximately $40 an ounce in the United States market. Some domestic producers were being paid on the basis of even higher European market prices.

Annual United States production of gold declined at an almost steady rate from about 2.1 million ounces in 1947 to 1.5 million ounces in 1964. Initiation of production from the Carlin deposit in Nevada brought domestic gold production up to about 1.8 million ounces in 1966. In 1967 production fell to about 1.5 million ounces as a result of labor disputes in most of the copper mining industry during the latter part of that year.

The Homestake gold deposit in South Dakota and the disseminated copper deposits of the West (from which gold is recovered as a by-product) accounted for most of the nation's gold supply from 1947 through 1964. Rising costs and the depletion of ore make it probable, unless new ore is found or the price of gold is increased even further, that the Homestake deposit will become economically exhausted within a few years. The recent price increase of gold has undoubtedly extended the life of this deposit, but continued rising costs will probably soon cancel the benefits of this price increase.

Gold consumption, although fluctuating, maintained a slow but more or less steady upward trend until 1958. The trend sharply accelerated after 1958 and rapidly widened the gap between consumption and production. This gap has been filled by imports. Growth in the manufacturing of jewelry as well as in aerospace and electronic uses apparently caused the abrupt change in trend. These uses of gold should continue to grow, and the projection of the trend since 1958 indicates an estimated 1985 consumption of between 12.8 and 13.9 million ounces. The use of gold substitutes could reduce consumption, while unforeseen technological changes resulting in an acceleration of demand could increase it. As far as gold is concerned, much depends on the future course of both monetary policy and the technology of gold use.

The Carlin and Cortez gold deposits should add substantially to future domestic production, compensating for decreased production from the Homestake deposits. Nevertheless, production at the present ($40 an ounce) price of gold is not expected to increase too much more than 2.8 million ounces by 1985, and could even decrease (with the

Table 20

ESTIMATES OF MINERAL GOLD RESERVES IN THE UNITED STATES

Date	Source	Reserves (million troy ounces)	
1955	(MF&P)	69.0	(*measured, indicated*, and *inferred;* 1944 estimate)
1962	(Min. Res.)	50.0	
1964	(I.C. 8325)	22.12	(*measured, indicated*, and *inferred;* including by-product gold ores)
1965	(MF&P)	20.0	
1965	(CDS)	20.0	(*measured* and *indicated*, including by-product gold ores)
1967	(CDS)	20.0	(*measured* and *indicated*, including by-product gold ores)
1968	(CDS)	54.0	(*measured* and *indicated*, including by-product gold ores)

Sources: MF&P = *Mineral Facts and Problems*, U.S. Bureau of Mines
CDS = *Commodity Data Summaries*, U.S. Bureau of Mines
I.C. = U.S. Bureau of Mines Information Circular

complete closing of the Homestake Mine), unless new large deposits similar to Carlin are found within the next 15 years.

Potential domestic reserves of gold are quite large, if the low-grade placer and disseminated deposits in the Western United States are taken into account. There are many dry placer deposits in the areas where low-cost water for profitable concentration and extraction of the gold are not presently available. Various techniques for dry concentration have been tried without success. The geologic character of individual deposits and the state of extractive technology have considerable influence upon the economics of mining, so that an estimate of the average price at which the various gold reserves could be profitably mined cannot be accurately forecast.

A rise in the price of gold to say $70 an ounce would undoubtedly stimulate the mineral industry to develop profitable extractive methods for placer and disseminated deposits, as well as causing many previously abandoned low-grade gold mines to reopen. Australia has stimulated gold production by making it tax-free. Canada has long provided outright subsidies to gold mining operations. The suggestion has been made that United States gold production could be encouraged and increased by raising the applicable depletion allowance from the present 15 percent to 30 percent. Other methods have also been proposed. Without further price increases or cost reductions, or new discoveries, currently known primary gold reserves will probably be exhausted before 1985. Reserves of by-product gold from base metal deposits, however, which presently supply a little less than a third of domestic production, will still be available.

Table 21

ESTIMATES OF MINERAL SILVER RESERVES IN THE UNITED STATES

Date	Source	Reserves (million troy ounces)	
1955	(MF&P)	763.4	(*measured, indicated,* and *inferred;* 1944 estimate)
1962	(Min. Res.)	750.0	
1964	(I.C. 8325)	645.8	(*measured* and *indicated;* includes by-product silver ores)
1964	(I.C. 8325)	1,194.8	(*measured* and *indicated* and *inferred;* includes by product silver ores; excluding copper deposits, reserves = 588.3)
1965	(CDS)	590.0	(*measured* and *indicated;* includes by-product silver ores, average grade of all reserves 0.303 of silver)
1965	(MF&P)	590.0	(*measured* and *indicated*)
1965	(MF&P)	1,430.0	(*measured, indicated,* and *inferred*),
1965	(MF&P)	52.7	(*measured* and *indicated* in silver ore, 85, including *inferred*)
1965	(MF&P)	5.3	(*measured* and *indicated* in gold ore, 4.0 including *inferred*)
1967	(CDS)	590.0	(*measured* and *indicated;* includes by-product silver ores)
1968	(CDS)	1,320.0	(*measured* and *indicated;* includes by-product silver ores)

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
I.C. = U.S. Bureau of Mines Information Circular

Silver reserve estimates made since 1950 have followed a pattern equally as variable as that of gold reserve estimates. In 1955, *Mineral Facts and Problems,* quoting a 1944 estimate, stated that the nation had approximately 760 million troy ounces of silver in the ground. By 1962, this had dropped to 750 million ounces and by 1964 had declined to less than 650 ounces of *measured* and *indicated* reserves, including by-product silver. If *inferred* ore reserves are added to this, the reserve estimate (as stated in *Information Circular 8325* of the U.S. Bureau of Mines) was nearly 1.2 billion ounces, including by-product silver. If copper ores containing silver were excluded, however, the nation's silver reserve dropped back to less than 590 million troy ounces. The latter figure was the amount stated as the nation's silver reserve in 1965 in the Bureau of Mines *Commodity Data Summaries.*

Price changes in silver have, of course, affected the reserve status of silver-bearing rocks. In 1968 the Bureau of Mines *Commodity Data Summaries* estimated *measured* and *indicated* reserves of silver in the United States, including by-product silver, at 1.3 billion ounces. This is approximately 500 million ounces higher than the 1944 estimate, despite the fact that from 1951 to 1967 the nation's mineral deposits yielded more than 600 million ounces of silver.

Estimated reserves of silver in the United States have been closely related to reserves of lead, zinc, and copper ores in which silver occurs as a co- or by-product of the more prevalent base metal. Reserve estimates have also varied according to subjective estimates of *indicated* and *inferred* reserves, and the annual ratios of new ore discoveries to ore mined out.

The increases in the price of silver since the early 1960's, particularly in 1967, have turned large amounts of low-grade rock into ore. Coupled with new ore discoveries, these new lower-grade reserves have more than compensated for the depletion of previous reserves through production since 1947. A 1944 estimate (published in 1955) showed total United States reserves of more than 760 million ounces of silver. Despite 1951 to 1967 production of more than 633 million ounces, 1968 reserves of *measured* and *indicated* ore were estimated at 1.4 billion ounces. Approximately one-half of these total silver reserves, however, consist of by-product silver associated with copper ore, most of which is in large low-grade disseminated copper deposits. These silver reserves are thus non-responsive in nature.

With substantial silver reserves literally tied to base metals reserves, increases in the demand for silver cannot be fully satisfied by increases in production unless there are also increases in the demand for the associated base metals. Primary silver ore accounted for less than 10 percent, and gold plus silver ore for slightly more than 10 percent, of the total 1965 reserve estimates. Considerations of future supply and demand relationships must, therefore, distinguish between responsive reserves of primary silver ore and non-responsive, by-product silver reserves.

Nevertheless, even if all of the presently estimated silver reserves could be produced to satisfy demand, they would be exhausted within ten years at present rates of consumption. Most domestic silver consumption since 1947 has been supplied by imports and releases from the United States Treasury.

Silver production and consumption followed slightly declining trends through 1960. Since that time, however, the trend of silver consumption has curved upward and, since 1963, at a sharply increased rate. Aerospace and electronic uses, increased photographic consumption, and demand from hoarders and speculators (who correctly anticipated a rise in the price of silver) have been the contributors to this accelerated demand. In 1967, total apparent consumption declined, but there were indications that a drop in speculative buying was behind the decrease. Silver production rose at a slow rate from 1960 to 1966 but fell in 1967 because of strikes in the copper mining industry.

A lower rate of increase in silver consumption than that of the 1963-1967 period is projected for the period to 1985. It is assumed that the recent changes in the price of silver and accelerated requirements caused by the Viet Nam War stiumlated demand to an excessive degree which will not be maintained at the same rate of increase in the future.

Projections of future consumption depend to a large degree on whether or not an economic substitute for silver used in photographic film is developed. In addition, the recent high prices for silver have caused an increasing use of silver-clad copper in electronic products, reducing the amount of silver required for a given product. Consumption in 1985 could range from 200 million ounces, if silver substitutes come into widespread use, to 330 million ounces if they do not. A median estimated range of about 250 million ounces in 1985 would seem a reasonable consumption forecast at the present time.

Much of the future growth in silver consumption will probably accrue from its use in electronics. This industry is characterized by rapid changes in technology and uses of different materials. Unforeseen technologic changes could sharply increase or decrease the demand for silver, changing the picture entirely.

The recent increases in the price of silver have turned lower-grade rock into ore and have stimulated production moderately. Most of the nation's new silver is being produced from ores which, until the recent price increases, owed most of their value to other metals, principally lead. A substantial rise in silver production will not occur in the future, therefore, unless and until new mines principally valued for silver are found and put into production. If metallurgical extraction problems are solved for the silver ore in the Calico district of Southern California, large open pit silver mines may be brought into being and will provide sharply increased domestic silver output.

Exploration for new silver orebodies is presently being carried out at an accelerated rate, and it can be anticipated (barring a severe decline in the price of silver) that some new mines will be found and will go into production within the next fifteen years. Depending upon the metal's price, the rate of depletion of known silver deposits, and the rate of discovery of new mines, 1985 silver production may range from 90 to 220 million ounces. A median production range of 140 million ounces is projected for 1985, on the basis of present exploration activity and price trends.

4. Industrial Minerals Reserves

The *Paley Report's* estimates of United States minerals reserves were not confined to metallic commodities, nor were the inaccuracies in the report confined to the metals. In 1950, the President's Materials Policy Commission estimated that the nation's reserves of asbestos were extremely small. In fact, no definite estimate was made because of the smallness of the reserves. From 1951 to 1966 nearly one million tons of asbestos were produced in the United States and by 1965 a material survey published by the United States Bureau of Mines estimated that the country had two million tons of asbestos reserves, half of which were in Vermont and half of which were in California. These included both *measured* and *indicated* reserves.

At the time of the *Paley Report* the only known domestic asbestos reserves of any size were in Vermont, and even these were small. United States production at the time came principally from only one mine in Vermont, with small intermittent output from Arizona and a few other states. As a result, no real estimate of asbestos reserves was made in 1950, other than to note that they were small.

The Bureau of Mines *Materials Survey* in 1952 estimated, on the basis of known producing areas, exploration drilling at the Vermont mine, and geological data, an *inferred* domestic reserve of 1.6 million tons of asbestos. Since 1958 the discovery and development of new asbestos deposits in Northern California, as well as continued development at other producing properties, have added substantially to domestic reserves. At the Jefferson Lake, California, property alone, an estimated 1.7 million tons of asbestos reserves were estimated from exploratory drilling data as of 1961. Other asbestos deposits occur and are being mined in the Coalinga area in the California Coast Ranges. At present, total domestic reserves of asbestos are probably on the order of five million tons or more. Reserve estimates made since 1959 have not fully taken into account these new reserves, particularly those in California.

Table 22

ESTIMATES OF ASBESTOS ORE RESERVES IN THE UNITED STATES

Date	Source	Reserves (million short tons)	
1950	(Paley)	"small"	
1952	(Mat. Surv.)	1.55	(*inferred*)
1959	(Mat. Surv.)	1.55	(*inferred*)
1962	(Min. Res.)	1.0	
1965	(Mat. Surv.)	2.0	(Vermont, 1.0; California, 1.0; *measured* and *indicated*)
1968	(CDS)	"moderate"	
1961	(Min. World)	1.7	(at Jefferson Lake alone)

Sources: MF&P = *Mineral Facts and Problems,* U.S. Bureau of Mines
CDS = *Commodity Data Summaries,* U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report)*
Mat. Surv. = *Material Survey,* U.S. Bureau of Mines
Min. Res. = *Mineral Resources of the United States,* U.S. Geological Survey
Min. World = *Mining World*

The *Paley Report* predicted that domestic asbestos consumption would in the future grow at a slower rate than that which had been experienced up to 1950.[166] Demand by 1975 was expected to increase 50 percent (to about 900,000 tons per year) over the 1946-1949 period when consumption averaged about 600,000 tons annually. Since then, despite the added production from the California deposits, domestic output of asbestos has remained far below consumption. Imports (90 percent of which came from Canada in 1962-1965) have compensated for the gap between domestic production and consumption. By 1985 production of asbestos could rise from 250,000 to 350,000 tons per year if presently operating deposits are expanded and/or new ones brought into production.

A large portion of the price paid by users for asbestos is the cost of transportation from mine to marketing or manufacturing facility. The Canadian deposits, in Quebec, are favorably situated with respect to the major markets in the Eastern United States, making competition from the deposits in the Western United States difficult. Favorably situated new discoveries of considerably larger size than those presently being used would be required to reduce to any great extent the present dependence of the United States upon imports of asbestos. Because asbestos is a relatively high-bulk, low-value industrial mineral, those deposits would have to be close to Eastern and Midwestern markets.

The 1950 reserve estimates of other non-metallic mineral commodities have not been as subject to question as those for asbestos. In 1950 the *Paley Report* estimated that the United States had approximately 250 million tons of potash reserves composed of solid potash containing a minimum of 14 percent potassium oxide and with a bed thickness of four feet in addition to brines averaging 2.5 percent potassium oxide.

Table 23

ESTIMATES OF POTASH AND SODIUM RESERVES IN THE UNITED STATES

Potash

Date	Source	Reserves (million short tons)	
1950	(Paley)	250	(approximate at + 14 percent K_2O, minimum bed thickness four feet, and brines averaging 2.5 percent K_2O)
1962	(Min. Res.)	400	
1964	(Landsberg)	400	(at + 14 percent K_2O)
1964	(Landsberg)	800	(at 10 percent K_2O)
1967	(CDS)	450	(*indicated*)
1968	(CDS)	450	(*indicated*)

Sodium

Date	Source		
1960		354 + 231 +	(in California and Wyoming, as sodium carbonate) (in California and Utah, as soldium sulfate)
1962	(Min. Res.)	"very large"	
1965	(MF&P, USBM Bull. 630)	650	(Soda ash in Wyoming)
1967	(CDS)	"large"	

Sources: MF&P = *Mineral Facts and Problems*, U.S. Bureau of Mines
CDS = *Commodity Data Summaries*, U.S. Bureau of Mines
Paley = President's Material Policy Commission (*Paley Report*)
Min. Res. = *Mineral Resources of the United States*, U.S. Geological Survey
USBM = U.S. Bureau of Mines

Urban and industrial expansion are placing increasing demands on limestone reserves. Future production will come from deposits at progressively greater distances from the consuming areas, at progressively higher costs. Limestone deposits which today are resources will become, and are becoming, reserves at a growing rate, particularly in the Western United States.

From 1951 to 1966, 38 million tons of potassium oxide in potash salts had been produced in the United States. By 1967, however, *indicated* reserves of potash had increased to 450 million tons. Nevertheless, the differences between the terms of the 1967 and 1950 potash reserve estimates and the relatively small tonnage produced compared to the original reserve tonnage estimates do not negate the validity of the *Paley Report* estimate. While approximately 250 million tons of potash containing plus 14 percent K_2O in the beds at least four feet thick, and brines averaging 2.5 percent K_2O, were estimated to exist in the United States by the *Paley Report* in 1950, exploration and development increased these reserves to 400 million tons in 1962 and an indicated 450 million tons in 1968.

Potash reserve estimates are variable according to grade. In 1964 Landsberg estimated domestic reserves at more than 800 million tons of potash at a grade of 10 percent or more K_2O equivalent. The average grade of ore mined has fallen in recent years, which has helped to maintain and increase potash reserves.

The *Paley Report* projected 1975 domestic consumption of potash at three million tons.[167] In 1966 consumption was just under four million tons. The consumption trend from 1947 to 1961, projected to 1975, ranges between three and four million tons, but actual consumption steepened sharply from 1961 to 1966. Whether this accelerated trend will continue or whether the rate of increase will drop to a more moderate figure will depend primarily upon agricultural demand. The consolidation of agricultural operations into fewer hands, more widespread recognition of the benefits of using fertilizer, and a more business-like approach to farming have caused the accelerated demand of recent years, aided by a corresponding increase in the use of fertilizers for home gardening and exports of fertilizer materials to less developed countries. More than likely, demand will not maintain its recent rate of increase but will begin to level off over the next few years as the areas of potential consumption become saturated.

Production and consumption of potash since 1947 have corresponded fairly closely. Beginning in 1964, however, consumption increased at a faster rate than production. The average grade of potash mined in the United States has fallen, requiring the mining of a greater tonnage simply to maintain, let alone increase, the production of potassium salts. Production from newly opened deposits in Western Canada has compensated for this gap between domestic production and consumption. Domestic potash reserves, however, even if the recent accelerated trend of consumption persists, should be adequate (though of lower grade than the Canadian ore) for more than forty years.

Canadian potash production is increasing as more deposits come on-stream, and it is expected to take an increasing share of the United States market. Projections suggest a domestic production range for 1985 of from 4.5 to 5.2 million tons, compared to a domestic consumption range of from six to 10 million tons of potash. The Canadian deposits are farther away from most of the United States markets than are the domestic deposits, however, and if consumption continues to increase at the 1960-1966 rate, the differential in transportation costs might allow domestic mines to expand production and compete successfully with the Canadian output. Domestic potash production might then rise more steeply to seven or eight million tons per year by 1985, depending upon demand.

The discovery of new potash deposits in the United States could also result in increased domestic production. In that portion of the Prairie Evaporites formation which lies within the United States (in North Dakota), deep potash deposits are known to exist and these might become significant in the future if techniques of solution mining are sufficiently improved.

Relatively small production since World War II of sodium minerals has tended to support, or at least has not detracted from, earlier mineral reserve estimates. Although the

Paley Report did not make estimates for reserves of sodium carbonate or sodium sulfate, reserves were estimated in 1960 for sodium sulfate at 354 million tons plus, in California and Utah. In the period from 1949 to 1967, only about 13 million tons of sodium sulfate were produced in the United States from natural deposits. Over the same period about 15 million tons of sodium carbonate were produced. By 1967 the *Commodity Data Summaries* of the Bureau of Mines simply set domestic sodium reserves at "very large" with no specific tonnage indicated.

Sodium carbonate (trona) is mined in Wyoming and California, and sodium sulfate is now mined in California, Texas, and Wyoming. Sodium mineral deposits of potential value are also associated with the oil shale deposits in Colorado, Wyoming, and Utah. Somewhat more than 23 percent of the nation's 1966 sodium carbonate production, and 45 percent of domestic sodium sulfate production, was mined from natural deposits. The country's remaining production of these two commodities was manufactured from rock salt (sodium chloride) or as a by-product in other chemical manufacturing processes.

The *Paley Report* did not list reserves of sodium minerals. Presently known reserves of sodium carbonate exceed 150 million tons at Searles Lake, California, and 650 million tons in the Green River area of Wyoming. Sodium sulfate reserves at Searles Lake have been estimated at 231 million tons, and Great Salt Lake, in Utah, contains an estimated 30 million tons. Numerous other deposits of undetermined size are scattered throughout the Western United States.

The 1967 *Commodity Data Summaries* lists reserves of trona (at 53 to 61 percent sodium carbonate) and sodium sulfate (at a grade of 60 percent) reserves as "large." Other reports have not made reserve estimates for sodium, other than to note that they are very large.

Exploration for trona in Wyoming has continued since 1960, and the development of new reserves has far outstripped production. The cost of producing manufactured sodium carbonate has increased, however, and current indsutry projections suggest that within the foreseeable future that will be a shift toward greater dependence upon natural sources of supply.

Nearly three-fourths of United States sodium sulfate consumption is in paper plants. Competition from by-product sources and transportation cost differentials have so far limited the number of profitable natural sodium sulfate deposits to those in relatively close proximity to areas of paper manufacture. Currently there are more known sodium sulfate deposits than there are outlets for production from them.

Domestic rates of consumption of sodium sulfate and sodium carbonate were more or less steady until 1958 and 1961, respectively, after which they began rising. Projected at the accelerated rates, the 1985 sodium sulfate and sodium carbonate consumption ranges are approximately 2.6 to 2.9 and 10.2 to 10.7 million tons per year, respectively. Based on a projection of the slower 1947-1965 rates, the 1985 consumptions should range from 1.8 to 2.2 and from 8.4 to 9.4 million tons per year each. A substitution of other materials (e.g., plastic) for kraft paper products could adversely affect sodium sulfate consumption. Mine production of sodium sulfate will probably vary in step with paper production.

Known sodium carbonate reserves are sufficient to supply demand at the projected 1985 rates for more than 30 years. Similarly, and disregarding location factors, sodium sulfate reserves are good for more than 90 years. Increases in demand through the development of new or expanded uses could, of course, change the picture. So also could shifts in the location of consuming industries.

Total known limestone reserves in the United States as such are overwhelming. Total *useful* limestone reserves, on the other hand, are limited. Known useful reserves are restricted to types having particular chemical and/or physical characteristics which make them valuable for specific uses. Useful reserves are further restricted, for most types of limestone, to their relative proximity to areas of present and foreseeable future consumption. Urban and rural development have removed some limestone deposits from reserves, placing a premium on other deposits which are sometimes at a considerable distance from the using areas (e.g., in Pennsylvania). The net result is that the cost of limestone has been increased by greater transportation costs, which constitute a large portion of the final price of limestone products.

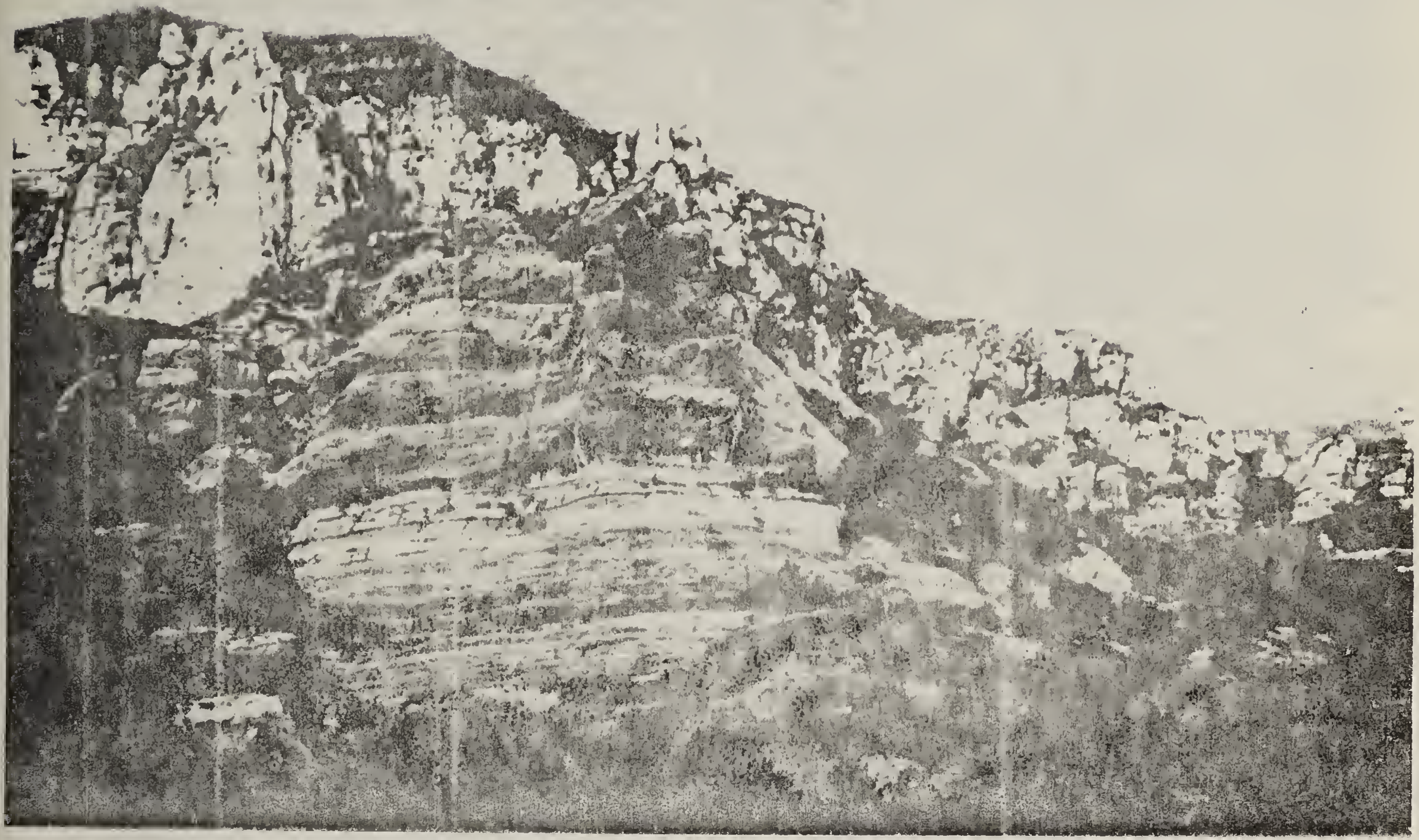


Fig. 81 - Area on the edge of the Colorado Plateau containing extensive limestone deposits now being utilized in the production of cement. As demand for construction materials has grown in various parts of the West, the utilization of undeveloped limestone deposits has increased.

D. SUMMARY

Various estimates have been made of the mineral reserves of the United States since 1947. These estimates have not been substantiated by subsequent production figures, nor have they agreed one with another. The reasons for the inaccuracies of mineral reserve estimates are basically two. First, they have been, and still are, based on geologic knowledge that is incomplete. Present geologic knowledge of the nation's minerals is in fact extremely limited.

Second, and perhaps even more important, estimates of valuable mineral reserves have been and are based on assumptions about future economic and technological conditions. Such assumptions have been notoriously erroneous. Coupled with the basic problem of forecasting future economic and engineering parameters is the additional problem that economic forecasts very often have a direct influence on the very items that they are predicting. For example, a forecast of high production will induce firms to increase productive capacity and produce more, thereby validating the forecast. Conversely, and yet similarly, a forecast of declining consumption may induce greater sales effort, thereby increasing consumption and refuting the forecast.

So it has been with mineral reserve estimates and so it is likely to be. In many instances (e.g., uranium), estimates of inadequate ore reserves to supply expected demand have stimulated exploration for additional reserves which have been found, thereby increasing reserves and invalidating the estimate. The converse is just as likely if reserves appear abundant or demand slight.

There have been changes in domestic mineral reserve estimates since 1947. Total reserves have increased for nearly all the nonfuel mineral commodities with the exception of tungsten, for which reserves have decreased. This generally rosy picture is somewhat misleading in that most of the reserve data include only slightly probable (*inferred*) reserves, the existence of which may or may not be substantiated by future exploration, development, cost increases, and price changes. Technology must be improved to allow profitable extraction of resources in the face of continually rising costs. Such "inferred" reserves generally constitute 50 percent or more of the total reserve estimates for the various mineral commodities, and their actual existence cannot be guaranteed. The highly probable and moderately probable (*measured* and *indicated*) ore reserves capable of satisfying increasing industrial demand for minerals over the next two decades are not as plentiful, then, as current estimates would suggest.

Given a favorable political and economic climate, new ore reserves will probably continue to be discovered and developed in the United States, and production will be maintained at rates in keeping with demand. If exploration and development are restricted in one form or another, however, *responsive* ore reserves could rapidly be depleted and the United States could easily become dependent upon foreign sources of supply as is now the case with a limited number of commodities.

Reserves of most of the non-metallic mineral commodities have been increased more than they have been depleted by production since 1947. Part of this has been through continued development of known deposits at operating mines. Increasing demand for and recognition of the value and potential uses of non-metallic mineral commodities has stimulated exploration and resulted in the discovery of many new deposits, largely in the Western United States. In most cases accurate reserve data are not yet available. Most of these deposits are currently in the *inferred* category because of economic rather than geologic factors, because of their greater distance from established markets than competing resources, and because they have simply not been developed. More and more of these deposits will become valuable mineral reserves as urban and industrial development expand and existing sources of production become exhausted or become more removed from areas of consumption.

For example, a brick manufacturing company in Phoenix, Arizona, ran short of a suitable brick clay supply in the early 1960's. Exploration followed, with the discovery and development of a clay deposit east of Tucson, Arizona, more than 125 miles away from Phoenix. Similarly, gypsum deposits near Winkelman, Arizona, were of relatively little value until 1960 when a wallboard plant using these deposits as a source of supply was constructed in Phoenix. The Winkelman deposits, more than 50 miles away, are now an essential source of supply for the Phoenix wallboard plant, and the wallboard plant is an essential market for what are now valuable gypsum deposits.

Sand and gravel pits are commonly considered unpleasant nuisances more than anything else. Yet adequate supplies of suitable sand and gravel have become so short in the Bay Area around San Francisco that these mineral commodities are hauled in from more than 100 miles away. The distance from the resource to the market has increased, resulting in an increased cost to the consumer. The same is true of many other industrial minerals used in construction. Suitable limestone deposits for cement manufacture have been considered so essential to future development that they have been acquired by some cement companies in Arizona more than 20 years in advance of anticipated need.

The total mineral resources of the nation and the West include both known and unknown volumes of specific mineral-bearing rock which may become ore at some future date but which are not presently proven to exist geologically or are not of sufficient grade to be considered ore. Less than 40 percent of the total in most published mineral reserve estimates is *measured*, useful ore, and in some cases less than 10 percent of the total reserves are *responsive* ore reserves. Many mineral commodity reserve estimates, therefore, have been generally misleading in that they have included large tonnages of rock which could not be relied upon to satisfy demand at any specific time.

Many economic relationships dictate whether a given mineral deposit is to be considered an actual or potential ore reserve. These relationships may change at any time through technological developments, changes in demand, in tax rates, in wage rates, in materials costs, in the cost of capital, and in many other factors. The degree to which domestic production is shielded from foreign competition sometimes makes the difference between ore reserve and resource for some mineral deposits. In some instances, federal stockpile policies may have similar effects.

Tax policies which require the payment of a property tax on mineral in place penalize the development of ore reserves, so that *measured* or *proven* reserves are not usually developed far in excess of immediate requirements. Under normal practice, new reserves are developed as old reserves are mined out, insofar as is possible, for a given deposit. In some deposits this requires considerable exploration, with marginal chances of success. For others, the process is more one of proving up what is already strongly suspected to exist. Known reserves thus change constnatly according to the rate of discovery, the amount of new ore, and the rate of production.

The recognition of impending future shortages of a mineral commodity or an increase in demand has spurred exploration (particularly since the *Paley Report* estimates) with the frequent development of additional reserves, which have in most cases increased more rapidly than they have been depleted by production. One cannot, in most cases, however, predict the rate at which new ore is discovered and developed, nor its amount, nor if it will be discovered at all. For example, despite strong demand, to date there have been no tin or platinum deposits of consequence found in the United States.

Ore reserves are generally developed not far in excess of the amount required to recover the initial investment plus a reasonable profit. Usually this involves an expected life for the deposit of from 10 to 25 years. For some large, easily explored deposits and for deposits requiring a very high original capital investment, the anticipated life may be longer. The development of reserves in excess of those required for profitable operation is penalized by prevalent tax laws, so that the total possible reserves of a deposit are rarely developed at one time.

Prudent mining practice dictates the maintenance of an exploration and development program of a size in keeping with profitable operations so that, hopefully, ore mined out is replenished by the discovery and development of new ore. Thus, *indicated* ore is further developed and becomes *measured* ore; *inferred* ore may become *indicated* ore; and new reserves of *inferred* ore may be estimated. The amount of new ore developed in a mine will vary from year to year according to the character of the deposit, or deposits, and the success ratio in discovery. Net reserves, of course, depend also upon the rate of mining.

Ore reserves in some deposits cannot be completely proven without excessive expenditures and, in a strict sense, remain *indicated* or *inferred* until they are proven by removal from the ground. The accuracy of many reserves is really only proven or disproven by mining, and reserve estimates are subject to constant fluctuation. In some cases, exploration drill hole information upon which estimates have been based may be completely misleading and subsequent development and mining may result in a drastic gain or loss in ore reserves. Mine fires involving the spontaneous combustion of massive sulfides exposed to air, flooding by underground water, and cave-ins may cause sudden losses of reserves just as a new blast in a drift heading may expose previously unknown ore and suddenly increase reserves.

Reserve estimates vary with the reliability given to the various categories of reserves and resources. Predictions of the adequacy or inadequacy of known reserves of a mineral commodity to satisfy future demand are generally given in terms of total or unspecified (as to category) reserves. These reserves rarely agree with subsequent estimates after deduction of depletion from mining because of the continued exploration for and development of new reserves. In addition, wars, depressions, and technological changes are relatively unpredictable factors which prevent accurate forecasts of the ability or inability of known reserves and resources to satisfy future consumption demands.

Orebodies are characteristically small and scattered in some mines, particularly in those of mercury, tungsten, and the precious metals. As a result, *measured* reserves may be quite small at any one time, but through continuing and successful exploration may be maintained ahead of mining. The prices of mercury and tungsten have fluctuated sharply and unpredictably in the past, resulting in a policy of developing only enough ore to get into quick operation and make a profit while prices are sufficiently high. In such deposits, therefore, most of the reserve estimates consist largely of *inferred* ore which hopefully will be found and mined.

The problems of ore reserve estimation are many. Numerous variables are involved in any one estimate and each of these variables in turn involves differing degrees of uncertainty, some greater and some lesser. The only thing certain about ore reserve estimates is that they are only estimates, and they are almost always wrong.

FOOTNOTES

143/ McKinstry, *op. cit.*, p. 470.

144/ *Ibid.*, pp. 471-472.

145/ *Ibid.*, p. 472.

146/ *Ibid.*, p. 470.

147/ D.H. McLaughlin, "Biological Factors in the Evaluation of Mines," *Economic Biology*, Vol. 34 (1939), pp. 589-621.

148/ W. Lindgren, "Geographical Features of Gold Production of North America," *A.I.M.E. Transactions*, Vol. 33, pp. 790-845.

149/ E. Seuss, *Die ZuKunft des Goldes*, Vienna (1877), p.

150/ A. Del Mar, *A History of the Precious Metals*, (1880).

151/ J.N. Faick, "Geology and Technology of some Natural Pozzalans in North Central California," *Economic Geology*, Vol. 58 (1963), pp. 702-719.

152/ *Ibid.*, p. 702.

153/ *Ibid.*, p. 700.

154/ *Commodity Data Summaries* (1967), p. 72.

155/ *Paley Report*, p. 31.

156/ *Ibid.*, p. 34.

157/ *Ibid.*, p. 34.

158/ *Resources in America's Future*

159/ *Ibid.*, p. 44.

160/ *Ibid.*, p. 914.

161/ *Commodity Data Summaries*, Washington: Bureau of Mines, U.S. Department of the Interior (January 1968), p. 72.

162/ *Ibid.*, p. 93.

163/ *Paley Report*, *op. cit.*, p. 94.

164/ *Commodity Data Summaries*, *op. cit.*, p. 155.

FOOTNOTES (Continued)

165/ H.J. Winters, *Concentration Ratios and Ease of Entry into Metals Markets* Tucson: University of Arizona (1968).,

166/ *Paley Report, op. cit.*, pp. 91-92.

167/ *Ibid.*, pp. 91-92.

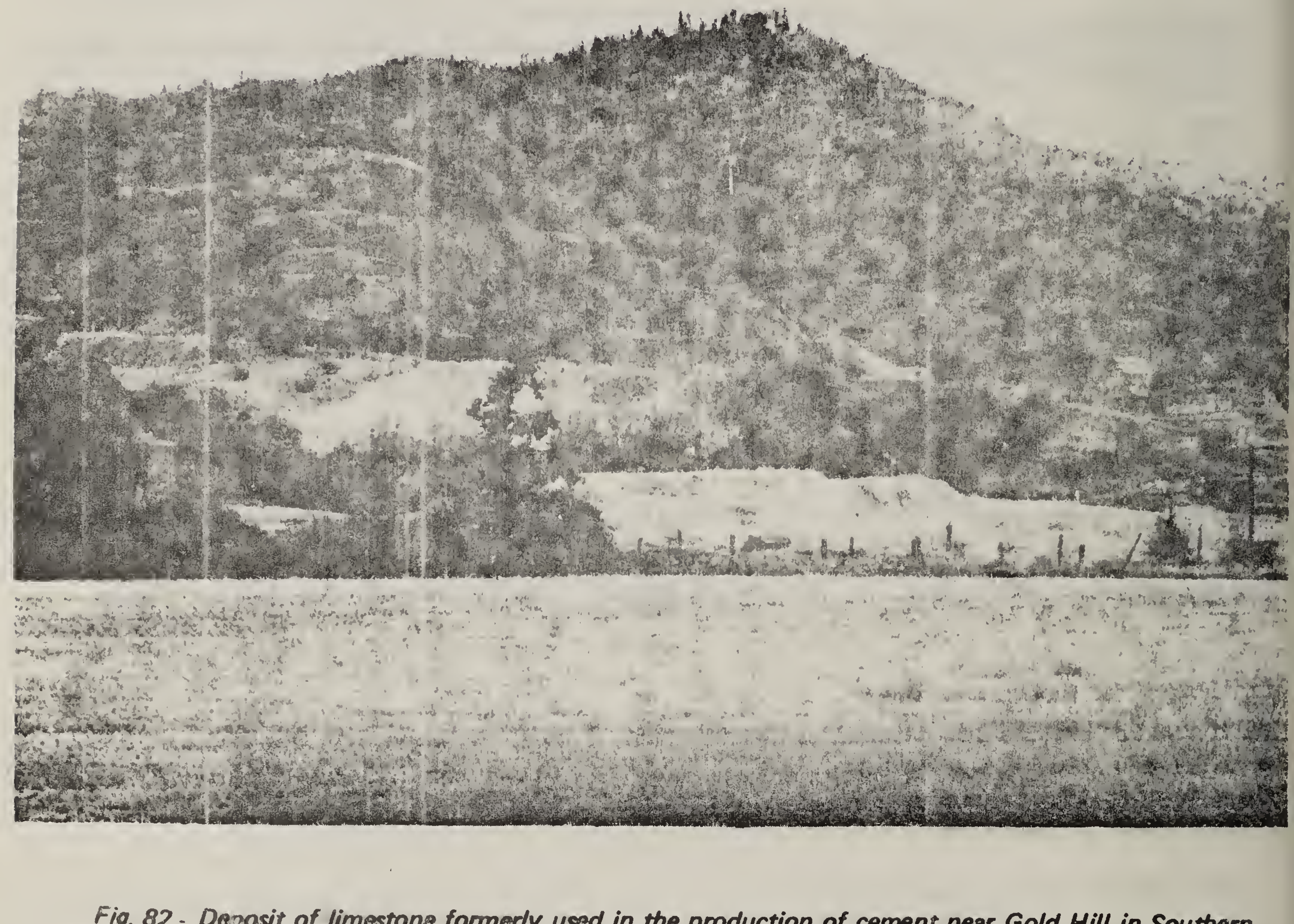


Fig. 82 - Deposit of limestone formerly used in the production of cement near Gold Hill in Southern Oregon. Although the mineral deposit remains unchanged, varying economic conditions have resulted in the halting of production operations and in effect have decreased national limestone reserves by the size of this deposit. For most industrial minerals, however, even the concept of national reserves is meaningless since markets are almost always local or regional.

CHAPTER 6

MINERAL RESOURCES ON THE PUBLIC LAND

Are certain public land areas likely to become targets for nonfuel minerals exploration and development before 1985?

A. MINERAL PRODUCING DISTRICTS AND PUBLIC LAND AREAS

1. California

The intensive development of mineral resources in the American West began on public lands in California. Public lands still cover a substantial area of the state. Of California's total area of more than 100 million acres, more than 44 percent is owned by the federal government. Of the total under federal ownership, slightly more than 42 million acres are in the original public domain, while about two million acres have been acquired.

The United States Bureau of Land Management and the United States Forest Service have been charged with responsibility for major portions of the public land in California. Approximately one-third of the public land (more than 15 million acres) in California is under the jurisdiction of the Bureau of Land Management. The Forest Service has direct jurisdiction over an even larger amount, however, approximately 20 million acres. The remainder of the public land in California is controlled largely by the National Park Service and the Department of Defense save for minor amounts, control of which is fragmented among numerous other federal agencies.

Most of the public land that is open to mineral resource utilization in California is located in the eastern and southeastern portions of the state. Considerable portions of that land geologically attractive for mineral utilization at the present time are still controlled by federal agencies. In the north, areas of the coast ranges and the Sierra Nevada are largely under the jurisdiction of the Forest Service with significant amounts of public land around the fringes of the Forest Service areas under the control of the Bureau of Land Management. Large areas of the Sierra Nevada and more mountainous areas in Central and Southern California are also under the jurisdiction of the Forest Service. Most of the area in the Mohave Desert region of Southeastern California that is not within restricted areas used by the Department of Defense, or within established national parks and monuments, is under the jurisdiction of the Bureau of Land Management. By far, the bulk of this is in the arid regions of Southeastern California.

Mineral development began in California with the production of mercury from the coast ranges and the mining of gold in the western foothills of the Sierra Nevada. Significant areas in both the coast ranges and the western foothills of the Sierra Nevada are still under the ownership of the federal government and are administered by the Bureau of Land Management. Those valley lands in which much of the early placer gold mining took place, however, have virtually all passed from federal ownership. Nearly all of the central valley of California now devoted to urban, industrial, and agricultural uses is in private hands.

Although the areas initially most productive of mineral resources in California have passed from the public domain, the areas in which existing mineral resources are being developed and the areas which have the greatest potential for future mineral resource utilization are still under the jurisdiction of the federal government.

These include the national forests in the mountainous regions of Northern, Central, and Southern California, areas in the southeastern Mohave Desert region administered by the Bureau of Land Management, some of the lands in the western foothills of the Sierra Nevada, the coast ranges, and areas in the northeastern part of the state near the Nevada border.

Table 24

FEDERAL LAND IN THE WESTERN STATES
As of June 30, 1966

State	Area Owned by the Federal Government (acres)	Percent of Total State
Arizona	32,450,805	44.6
California	44,366,704	44.3
Colorado	24,038,439	36.2
Idaho	34,015,623	64.3
Montana	27,638,884	29.6
Nevada	60,971,262	86.8
New Mexico	26,726,733	34.4
Oregon	32,184,820	52.2
Utah	35,180,735	66.8
Washington	12,553,655	29.4
Wyoming	30,004,331	48.1
Sub-total:		
Total United States:	764,762,128	33.7

Source of Data: United States Department of the Interior, Bureau of Land Management, *Public Land Statistics, 1967*. p. 11

There are a number of large areas within economic distance of both California's major metropolitan markets (i.e., San Francisco and Los Angeles) that are still under the control of the federal government and which are suitable for the present and future utilization of mineral resources, including both industrial minerals and metallics. Probably the most likely areas for future mineral resource utilization in California, however, are in the Mohave Desert (which is still largely under the control of the Bureau of Land Management) and in the Sierra Nevada. Scattered areas throughout, the coast ranges are also geologically attractive under current and expected conditions. Thus, federal land policies with respect to mineral resources and their utilization should have a definite future impact upon the development of mineral resources in the state of California, just as they have since before 1850.

2. Nevada

Nevada was the second Western state to experience substantial mineral resource development. The state still contains the largest amount of public land area in the 48 contiguous United States. Of Nevada's total area of slightly more than 70 million acres, nearly 87 percent is under federal ownership and control. Most of this (nearly 48 million acres) is under the jurisdiction of the Bureau of Land Management. About five million acres are under the control of the Forest Service, while other substantial acreages of the state are administered by the Atomic Energy Commission, the Defense Department, the National Park Service, the Bureau of Sports Fisheries and Wildlife, and the Bureau of Reclamation.

With nearly all of Nevada still owned by the federal government, it is inevitable that many of those areas of the state most suitable geologically and economically for future mineral resource utilization are within areas directly affected by federal land policies. To this date, comparatively little of Nevada's land has passed to private ownership even in those areas on the eastern edge of the Sierra Nevada which were initially explored and developed for their mineral resources in the 1800's. These areas, extending from Reno on the north as far south as Tonopah and Goldfield, are still attractive for mineral resource utilization. These areas are largely controlled by the federal government through the Bureau of Land Management. Those mining areas in the eastern part of the state, near Ely and Pioche, are also largely under the jurisdiction of the Bureau of Land Management. The same is true of those areas in the northern part of the state near Carlin and Battle Mountain. Even in Southern Nevada, areas around the Las Vegas metropolitan area which are both geologically and economically appropriate for the future development of both metallic and non-metallic mineral resources are, in most respects, under the administration of the Bureau of Land Management.

Areas of Nevada under the control of the Forest Service are scattered mostly throughout the central and northern parts of the state. These areas, particularly in the east and

Fig. 83 - High in the Sierra Nevada between California and Nevada. The mountains themselves are still under federal ownership as are many of the areas along the eastern and western edges of this massive intrusion where early mineral resources were developed. Virtually all other mountain ranges in the West are also owned by the federal government with most high mountainous areas administered by the United States Forest Service.

northeast, are also favorably situated for the future development of mineral resources. The same is true of those areas controlled by the Bureau of Reclamation and the National Park Service in far Southern Nevada. The mineral potential of those parts of Nevada under the control of the Bureau of Sports Fisheries and Wildlife and the Atomic Energy Commission is virtually unknown.

3. Montana

From early activity in California and Western Nevada, development of the mineral resources of the West spread rapidly throughout many of the Western States. One of the earliest regions to gain attention was the mountainous region of Western Montana. Today more than 27 million acres of Montana's total 93 million acres (nearly one-third of the state) are owned by the federal government. Of this total, only about eight million acres are administered by the Bureau of Land Management. By far the greatest portion of the acreage under the control of the Bureau of Land Management is in the eastern agricultural regions of the state, although there are significant Bureau of Land Management areas in the mineral-producing southwestern region and scattered throughout the rest of the state as well.

The Forest Service is responsible for the administration of nearly 17 million acres in Montana, and most of these are in the western part of the state in areas with a high potential for future mineral resource development. Virtually the entire portion of Montana lying west and southwest of Helena, the state capital, is under the jurisdiction of the federal government, largely in lands administered by the Forest Service but also in lands administered by the Bureau of Land Management. Most of the private land in this part of Montana is in the river valleys, reflecting the early importance of placer mining and agricultural activity. There is little doubt that many areas in the western part of Montana that are most attractive both economically and geologically for future nonfuel mineral resource utilization are now held by the federal government.

4. Idaho

A similar situation exists in the neighboring state of Idaho, which also saw early mineral development for precious metals and where existing resources of base metals and phosphates are likewise important. Nearly two-thirds of Idaho's 53 million acres are owned by the federal government. Of the total of approximately 34 million acres under federal ownership in Idaho, more than 20 million acres are under the supervision of the Forest Service. Nearly all of the remainder (i.e., more than 12 million acres) is administered by the Bureau of Land Management.

Most of the land administered by the Bureau of Land Management in Idaho is in the southern part of the state with a particularly heavy concentration in the southwest. The state's Forest Service land, on the other hand, is mostly in the central pan handle and in the northern part of the state, although there is also substantial Forest Service land along the eastern border with Wyoming. The location of the land that has passed to private ownership in Idaho reflects the early development of agricultural activity on the east, in the Idaho Falls and Poctello areas (where there is comparatively less federal land ownership), and the development of mineral resources in the Coeur d'Alene region of far Northern Idaho (where there are also substantial amounts of private land). The development of agriculture on the western border of Idaho is also reflected in the relatively larger percentage of private land along the Washington and Oregon borders.

A large part of the national forest area in Idaho is in the mountainous region created by the Idaho Batholith. The interior of this intrusive igneous area has been (in the past) relatively unattractive for the development of resources of base and precious metals. Nevertheless, the development of new mineral resources associated with the interiors of large igneous intrusions rather than with the fringes of such rock masses could make large areas of Central Idaho now under the jurisdiction of the Forest Service attractive for future mineral utilization. There also remain significant areas in the Coeur d'Alene district that are under the jurisdiction of the Forest Service and which are still (and perhaps even more) suitable geologically and economically for base and precious metals occurrence.

In Eastern Idaho, that portion of the state that falls within the western phosphate field is currently both geologically and economically attractive for mineral resource development. While the amount of private land in this region is comparatively high, there remain sufficiently large areas under the control of both the Forest Service and the Bureau of Land Management to make federal land policies significant in the development of the mineral resources of this part of the state.

Parts of Western Idaho now controlled by the Forest Service and the Bureau of Land Management fall within the Columbia Plateau region, an area covered by extensive formations of extrusive igneous rock. Heretofore, these areas have been relatively unattractive for minerals exploration. With the development of methods for mineral detection at depth, however, and with the growing significance of regional geologic studies, there is little doubt that the Columbia Plateau could become one of the West's foremost areas of mineral resource utlization within the next two decades. As a result, federally owned and controlled areas in Western Idaho may also become significant in the mineral resource picture of the state.

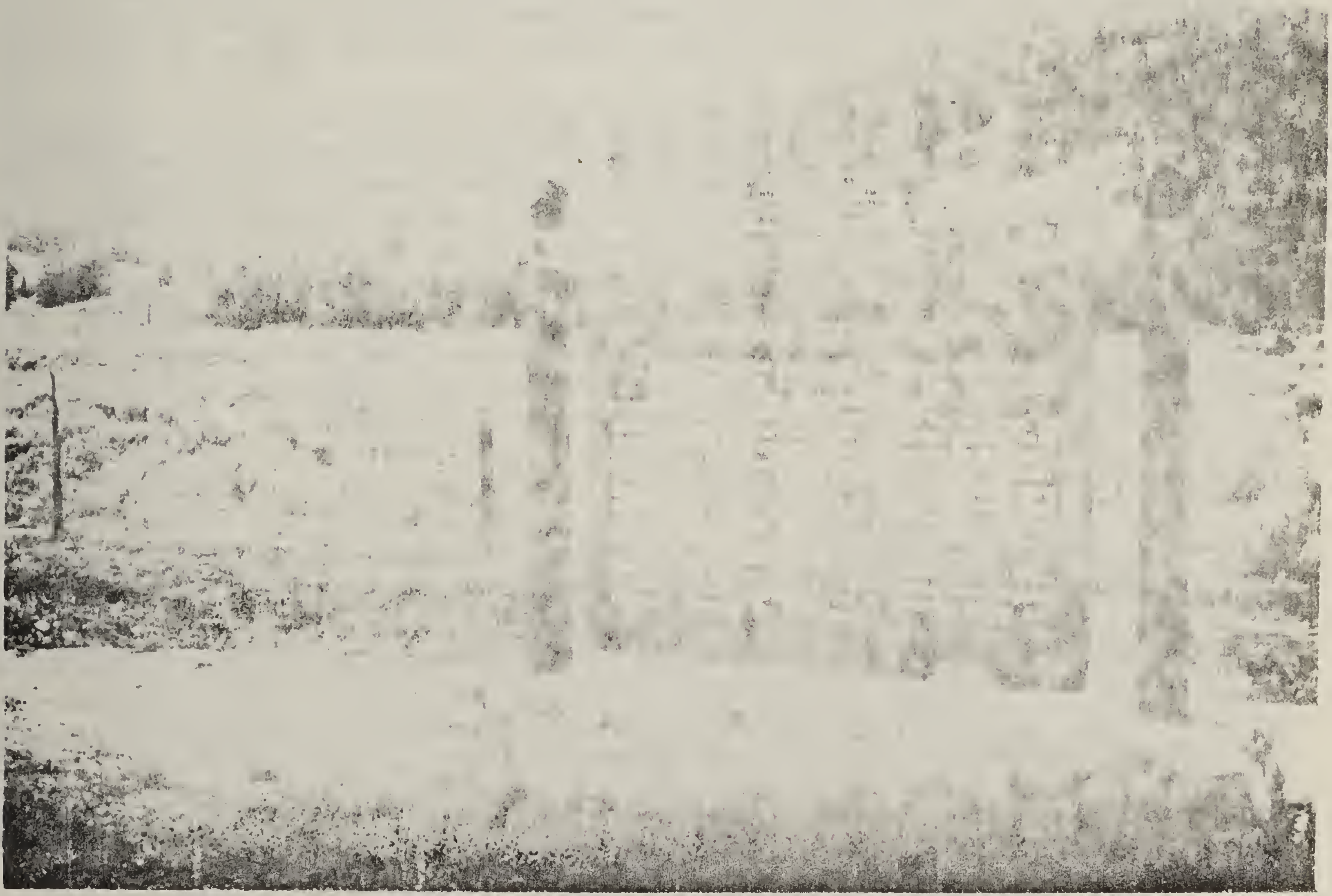


Fig. 84 - Mountainous area in Western Montana typical of the forested areas in both Idaho and Western Montana that are owned by the federal government and supervised by the Forest Service. Many such areas contain known mineral resources and have yielded substantial amounts of mineral production. In other areas, mineral resources are relatively unknown and undeveloped.

5. Washington

The development of mineral resources in the Pacific Northwest, in Oregon and Washington, has been relatively slight compared to the development that has taken place in the remainder of the West. This has been largely caused by the extent of the Columbia Plateau volcanics which cover and hide potentially valuable mineral resources, as well as by the extensive vegetation cover on the Pacific slope of the Cascades. Agriculture and urban development have been far more important in these two states, and the existing pattern of land ownership reflects this development.

Washington shares with Montana the distinction of having considerably less federal land within its borders than the other Western States. Approximately 29 percent of Washington's nearly 43 million acres are under federal ownership. Most of this land is in the Cascade Mountains in the central portion of the state and in the mountainous region along the northern border with British Columbia. Of Washington's more than 12 million federal acres, approximately 10 million are under the jurisdiction of the Forest Service, with only a quarter of a million acres administered by the Bureau of Land Management. The National Park Service, largely in Mt. Rainier and Olympic National Parks, controls far more land (over one million acres) in Washington than does the Bureau of Land Management.

Most of the land that is administered by the Bureau of Land Management in Washington is in scattered small acreages throughout the eastern and northeastern portions of the state, mostly north of the Columbia Plateau and along the eastern slope of the Cascades. Most of the Forest Service land, on the other hand, is in the west central portion of the state, extending from the Columbia River on the south to the border with British Columbia on the north and covering virtually all of the Cascade Range. The Forest Service also controls relatively small acreages in the northeastern portion of the state and on the Olympic Peninsula in the northwest.

Although in the past the most conspicuous utilization of Washington's nonfuel mineral resources has been in Eastern Washington, other areas of the state have also had significant mineral resources and still possess a high potential for future mineral resource development. Undoubtedly one of the most geologically attractive areas for future mineral resource discovery in Washington is in the North Cascades region. In the past there has been significant mineral industry activity in that region because of its known resources of precious metals. The potential for the area's future, however, involves deposits of non-ferrous base metals as well as precious metals. Because most of the region is under federal control, federal land policies will have (and have had) a significant impact on the utilization of the mineral resources of the Cascades area of Washington.

6. Oregon

Although gold placer deposits in the southern part of Oregon were among the earliest mineral resources to be developed in the West, the other mineral resources of the state have been left largely untouched. A major reason for this has been the distinct geologic and climatic conditions that exist within the state. These conditions have also been reflected in the existing pattern of federal and private land ownership in Oregon. Of the state's 62 million acres, a little more than half is still under the ownership of the federal government. The federal acreage is mostly in areas administered by the Bureau of Land Management and the Forest Service. Of the more than 32 million acres under federal ownership in Oregon, approximately 16 million acres are administered by the Bureau of Land Management while about 15 million acres are under the jurisdiction of the Forest Service. While most of the Forest Service land is located in the western portion of the state in the Cascade and Coast ranges, significant amounts of Forest Service land are also located in the northeastern part of the state. Most of the area under the jurisdiction of the Bureau of Land Management is in the central and southeastern portions of the state.

At the present time, Oregon's principal known mineral resources are found in areas that are largely under non-federal control. The state's largest known metallic mineral deposit, a nickel-bearing laterite deposit near Riddle, is in an area of essentially private land ownership. The state's major industrial minerals deposits are also for the most part in private land areas. The former gold producing areas in the southern part of the state are mostly in areas that are administered at the present time by the Bureau of Land Management and the Forest Service, but these deposits are generally inactive as current sources of significant mineral production.

A large part of Eastern Oregon is covered by the extrusive volcanics of the Columbia Plateau. Because the underlying resources are covered by varying thicknesses of apparently barren volcanics, in the past the development of mineral resources in this area has been greatly neglected, and the actual mineral potential of the region is virtually unknown. In the future, however, there is little doubt that this area will become increasingly attractive as a site for mineral exploration. The large areas controlled by both the Forest Service and the Bureau of Land Management in the Columbia Plateau region of Oregon, therefore, make federal land policies of extreme significance to the development of the mineral resources in the eastern part of the state.

Fig. 85 - The North Cascades region of Washington, almost completely owned by the federal government. Although recent utilization of mineral resources in this and similar areas of both Oregon and Washington has been slight, they were the locale of many early precious metal operations and their geologic potential as future sources of base metals is high.

In Western Oregon, along the Pacific slope of the Cascades, Forest Service policies, in particular, could become of vital importance in the development of laterite deposits such as the deposit at Nickel Mountain near Riddle. The development of technology for the effective utilization of such laterites could make this Pacific slope area of increasing significance in the nation's mineral resource picture over the next two decades. Furthermore, the growth of population in the valley of the Willamette River, in Western Oregon, could make the nearby areas in the Cascades (now controlled largely by the Forest Service) of increasing economic as well as geologic attractiveness for the development of industrial minerals resources. The same is true of the Cascade Range areas controlled by the Forest Service in Washington where the growth of population in the Seattle-Tacoma area and elsewhere around Puget Sound would make the development of industrial minerals resources in areas now controlled by the Forest Service of increasing importance.

7. Colorado

Outside of the Pacific Northwest, one of the earliest states to undergo economic and mineral resource development was Colorado. The state is almost a smaller scale replica of the United States west of the Mississippi River, with its eastern half lying on the Great Plains and its western half lying in the mountains and plateaus that are common throughout the area west of the 105th Meridian. The geographic division of Colorado is reflected in the pattern of land ownership in the state. A little more than one-third of Colorado's 66 million acres is under the control of the federal government. Virtually all of this federal acreage lies in the western half of Colorado, west and southwest of Denver. Of the total of more than 24 million acres under federal ownership and control in the state, more than 14 million acres are under the jurisdiction of the Forest Service, while approximately eight million acres fall under the supervision of the Bureau of Land Management. There are also significant acreages in the state under the control of the Department of Defense and the National Park Service.

Most of Colorado's land that is under the control of the Forest Service is in the central and west-central portions of the state, in the Rocky Mountains. Some significant acreages under Forest Service control are also located in the southwestern portion of the state, on the Colorado Plateau. Most of the areas administered by the Bureau of Land Management are scattered throughout the western portion of the state with large, substantially contiguous, located areas on the northwestern plateaus. Virtually all of Colorado east of the 105th Meridian is under non-federal ownership.

Most of those areas of Colorado presently known for their existing nonfuel mineral resources are in or adjacent to lands under the jurisdiction of the Forest Service. There are also significant known mineral resources in areas controlled by or adjacent to acreages under the administration of the Bureau of Land Management. These resources include both the precious and base metals deposits of the belt that extends across the Front Range of the Rockies and southwest through the San Juan region of the state. The uranium-rich regions of the Colorado Plateau and Western Colorado are in areas largely administered by the Bureau of Land Management, but are also adjacent to areas controlled by the Forest Service.

There is little doubt that the future development of mineral resources in Colorado will be even more affected by public land policies than in the past. This is true not only of those areas which have already produced base and precious metals and uranium, but also the Piceance Basin region of Northwestern Colorado, the so-called oil shale district. This area, now largely under the control of the Bureau of Land Management, has perhaps one of the most significant potentials for future mineral resource development in the state. This is not to deny, however, the importance of development in areas presently administered by the Forest Service in the Rocky Mountains and by both the Forest Service and the Bureau of Land Management on the Colorado Plateau.

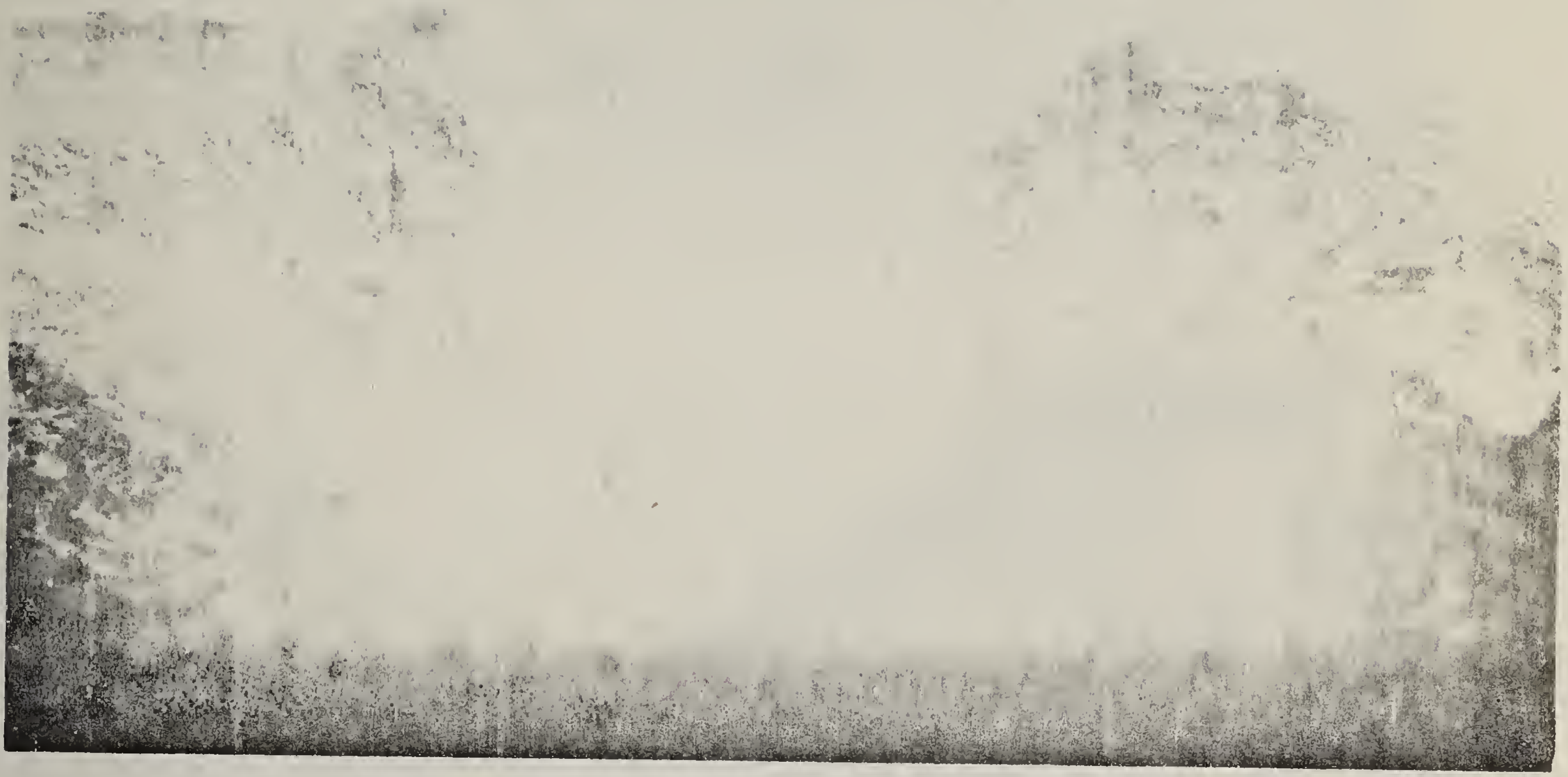


Fig. 86 - The Front Range of the Rocky Mountains in Central Colorado. This area, rich in metallic mineral deposits, is still largely owned by the federal government and controlled by the Forest Service. Large areas of Colorado west of the Rockies are under the administration of the Bureau of Land Management.

8. Utah

The physical geography and historical pattern of settlement and development of Utah are also reflected in its current land status. Of Utah's nearly 53 million acres, two-thirds are owned by the federal government. Of the more than 35 million acres owned by the United States in the state, by far the greatest portion (nearly 23 million acres) is under the jurisdiction of the Bureau of Land Management. The greatest portion of the remainder (some eight million acres) is under the jurisdiction of the Forest Service. Significant acreages within the state are also controlled by the Department of Defense, the National Park Service, and the Bureau of Sports Fisheries and Wildlife.

Most of the Forest Service land in Utah is in the central portion of the state in a belt which follows the chain of mountains ranges that extend from the southwestern corner of the state through the central portion to the Wyoming and Idaho borders. The bulk of the land supervised by the Bureau of Land Management is found in the eastern and southeastern portions of the state, on the Colorado Plateau, as well as in the basin and range area in the western portion of the state, in what is often referred to as the Great American Desert. Most of the private land presently held in Utah is found in the valleys of the central portion of the state.

Significant mineral resource utilization in Utah in the past has been scattered throughout the state. The earliest resources to be developed were in proximity to the larger population centers near the Great Salt Lake. These areas are for the most part at present under private ownership, although significant mineral resources in the mountainous areas are either on or adjacent to acreages administered by the Forest Service. In the southeastern portion of the state, the area around Moab is largely under the jurisdiction of the Bureau of Land Management with scattered areas of relatively minor importance (for known mineral resource utilization) under the control of the Forest Service. Most of the uranium production in Utah's portion of the Colorado Plateau, as well as the significant potash and phosphate developments in both Southeastern and Northeastern Utah, are in areas largely under the control of the Bureau of Land Management.

Fig. 87 - Mountainous area in Northern Utah under the jurisdiction of the Forest Service. Most of the mountain ranges in the state are federally owned and supervised by the Forest Service. The development of nonfuel mineral resources in such areas has been sparse, although their geologic potential is high. Most recent mineral development in Utah has been on lands administered by the Bureau of Land Management in the southeastern part of the state.

It seems most likely that the future development of the nonfuel mineral resources of Utah will take place in both the mountainous regions of the north-central part of the state that have in the past been known for their base and precious metal deposits (and which are currently controlled or influenced by the Forest Service) as well as in the eastern portion of the state, where the development of industrial minerals deposits will proceed on lands controlled or influenced by the Bureau of Land Management. The mineral resources of the western part of the state are in many respects unknown, but there is still a high potential for development of both base and precious metal resources in those areas currently administered by the Bureau of Land Management.

9. Wyoming

Wyoming in many respects is similar in its pattern of land ownership to Colorado. The eastern portion of the state on the edge of or directly on the Great Plains is largely under private ownership while the western portion of the state is largely under federal control. Of Wyoming's 62 million acres, a little less than half (48 percent) is owned by the federal government. Of the 30 million acres of Wyoming land that are held by the federal

Fig. 88 - Public land in Western Wyoming controlled by the National Park Service. Most known nonfuel mineral resources in the state are in the southwestern part of the state on lands supervised by the Bureau of Land Management.

government, approximately nine million acres are administered by the United States Forest Service, while the Bureau of Land Management is responsible for more than 17 million acres. The National Park Service (largely in Yellowstone National Park and Grand Teton National Park) controls over two million acres of Wyoming land.

Nearly all of the Forest Service land in Wyoming is in the mountains in the western portion of the state, but there are some scattered areas in the higher mountain ranges in the central part of the state that are also included under that agency's jurisdiction. A relatively minor acreage in the eastern portion of the state, on the edge of the Black Hills of South Dakota, is also controlled by the Forest Service. Most of the land in Wyoming under the control of the Bureau of Land Management extends in a wide belt through the west-central portion of the state, from the Utah and Colorado borders on the southwest to the Montana border in the central part of the state on the north.

Most of Wyoming's nonfuel mineral resource development to date has been in the southwestern portion of the state in areas administered by the Bureau of Land Management. This includes the phosphate resources of the western phosphate field in the extreme southwest as well as the known uranium and iron resources of the state. Those areas of Wyoming administered by the Forest Service have been relatively unimportant so far with respect to the development of the state's nonfuel mineral resources. This has been principally because the areas under the control of the Forest Service are in those mountain ranges formed by intrusive igneous masses which in the past have been geologically unattractive in themselves for base and precious metals exploration as well as industrial minerals development.

In the future development of Wyoming's mineral resources, it is likely that the most significant developments will be in those areas presently administered by the Bureau of Land Management. Thus, the land policies of the federal government may be expected to have a strong impact on the development of the state's nonfuel mineral resources.

10. New Mexico

For the most part, the development and utilization of mineral resources in the West came last to the Southwest, to Arizona and New Mexico. The relatively late development of that area and the intensity of resistance by the Indian tribes of the Southwest reflects the present status of land ownership in the area. Arizona has somewhat the greater amount of federal land than does New Mexico, with New Mexico's land ownership also being affected by the same geographic influences that shaped the pattern of land ownership in Colorado and Wyoming east of the 105th Meridian.

Of New Mexico's nearly 78 million acres, a little more than one-third is owned by the government of the United States. Most of this land is in the western portion of the state, west of the Great Plains, but large areas in the southeastern part of the state, in the Permian Basin region adjoining Texas, are still under federal ownership. Of the nearly 27 million acres of federal land in New Mexico, approximately 13 million acres are under the control of the Bureau of Land Management, with about six million acres under the jurisdiction of the Forest Service. The state also contains significant acreages that are under the control of the Department of Defense and the National Park Service.

Most of the area administered by the Forest Service is in the mountainous regions of the north-central and southwestern parts of the state. Those areas administered by the Bureau of Land Management are largely west of the Rio Grande and cover virtually all of Western New Mexico except for those areas in Indian reservations and national forests. Another significant block of acreage in the Permian Basin area in the southeastern corner of the state is also supervised by the Bureau of Land Management.

Most of the development and utilization of nonfuel mineral resources in New Mexico in the past has been in those areas under federal ownership. Earliest development was of the copper and precious metal deposits in the southwestern portion of the state. These areas at present are largely controlled by either the Bureau of Land Management or the Forest Service, although in areas of early development there are now substantial private holdings. New Mexico's potash resources in the Permian Basin around Carlsbad in the southeast are on land held primarily by the federal government with only limited and relatively minor private holdings.

More recent development of the state's nonfuel mineral resources has been in the north and includes the development of uranium resources in the northwest, on the Colorado Plateau, and in the north-central mountains where molybdenum resources have been of importance. In Northwestern New Mexico, in the uranium producing areas around Grants, development has been largely on lands controlled by the Bureau of Land Management, although there are significant acreages of Forest Service land nearby. In the northern mountains, the development of molybdenum resources has been in areas principally controlled by the Forest Service.

The future development of New Mexico's metallic and non-metallic mineral resources will probably come in those areas presently controlled by the Bureau of Land Management and the Forest Service. Thus, future public land policies will be of vital importance to the state's nonfuel mineral resource utilization.

Fig. 89 - Public land in the Permian Basin region of Southeastern New Mexico. Here, most known mineral resources are found at considerable depth. In the western and northern portions of the state, known mineral deposits are generally closer to the surface and may be mined more readily by open pit methods.

11. Arizona

As in virtually all of the other Western States, the existing pattern of land ownership in Arizona reflects both the physical geography of the state and the early pattern of settlement and economic development. Of Arizona's nearly 73 million acres, almost 45 percent (32 million acres) are owned by the federal government. Considerable portions of the state, however, are also administered by the federal government as trust territories for various Indian tribes. Of the 32 million acres owned and controlled directly by the federal government in Arizona, approximately 13 million acres are administered by the Bureau of Land Management while 11 million acres are under the jurisdiction of the Forest Service. Significant areas of the state are also under the control of the National Park Service, the Bureau of Sports Fisheries and Wildlife, and the Department of Defense.

Most of the nonfuel mineral development in Arizona to date has been in the southeastern portion of the state, on lands where there are scattered sections administered by the Bureau of Land Management as well as areas controlled by the Forest Service. Most of the land now controlled by the Bureau of Land Management in Arizona, however, is in the western portion of the state where mineral resource development to date has been limited. Most of the national forest land in the state is in a belt that extends from the

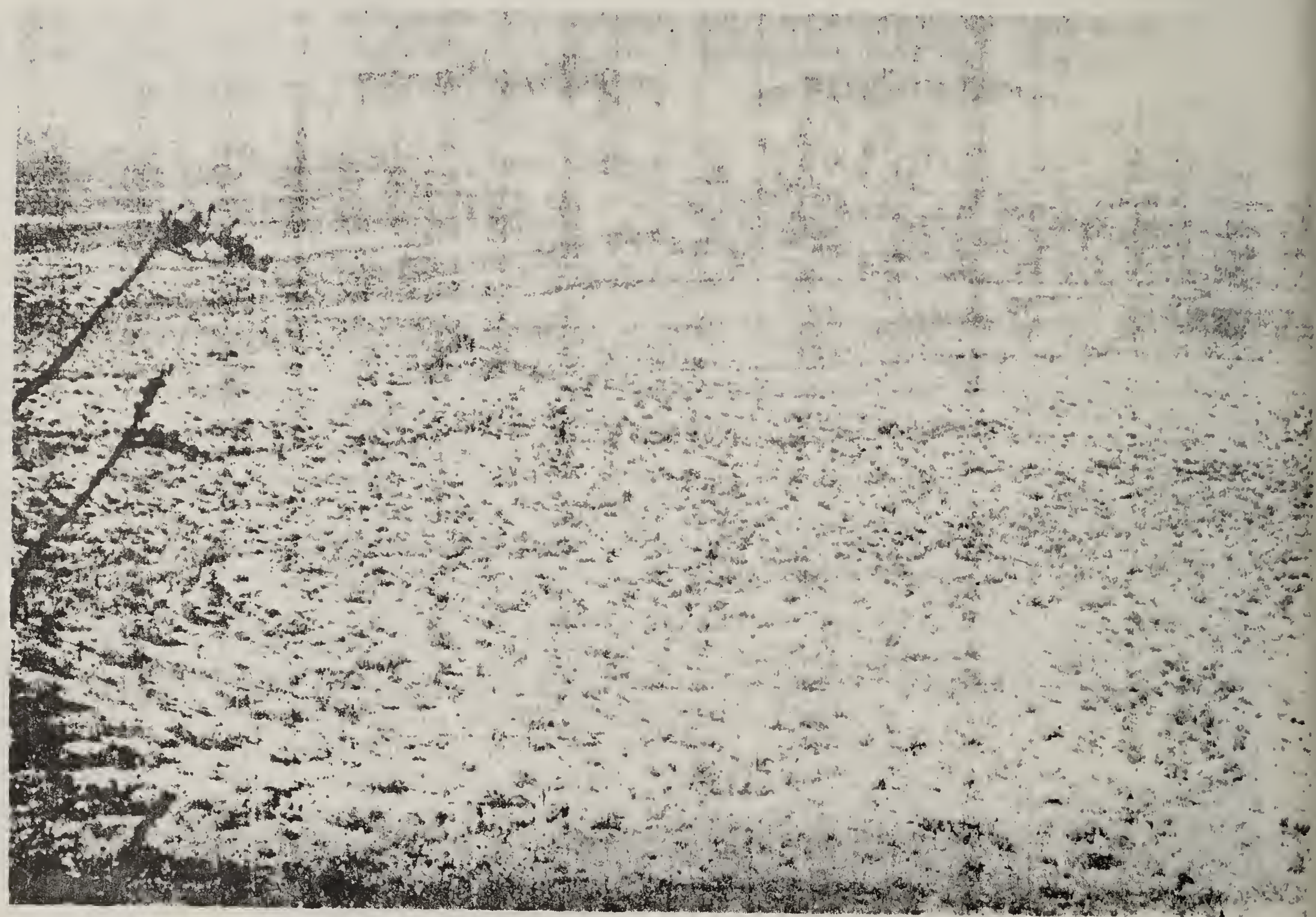


Fig. 90 - Basin and range topography on public lands in Southern Arizona. Most of the public land areas in the state, including those supervised by both the Bureau of Land Management and the Forest Service, possess high geologic potentials for future mineral resource development.

eastern border with New Mexico northwest along the edge of the Colorado Plateau to the vicinity of Grand Canyon in the northwestern part of the state. There are also scattered national forest areas in Southeastern Arizona, in scattered mountain ranges formed by intrusive igneous masses.

Although originally under federal ownership, most of the existing mineral producing areas in Arizona are now on privately held lands in the southeastern and central portions of the state. There also has been some development, however, on scattered Bureau of Land Management acreages as well as around the fringes of Forest Service lands. One of the greatest areas for potential mineral resource development in the state, however, lies in the west, adjacent to the Colorado River in the basin and range district now held by the Bureau of Land Management. These lands, as well as lands currently held by the Forest Service adjacent to producing copper districts in Southeastern Arizona, are undoubtedly the most attractive both geologically and economically for future mineral resource utilization in the state.

Throughout the entire Western United States, mineral development in the past has been largely on lands owned or controlled by the federal government. Development on private and state lands has been comparatively less, although state lands as well as federal lands have covered a significant part of the region's mineral resources. These areas that seem at present to be most suitable, both geologically and economically, for future mineral resource utilization in the 11 Western States are mostly on federal land controlled either by the Bureau of Land Management or the United States Forest Service. Public land policies will therefore be of vital importance in the future use of the mineral resources of this westernmost third of the nation.

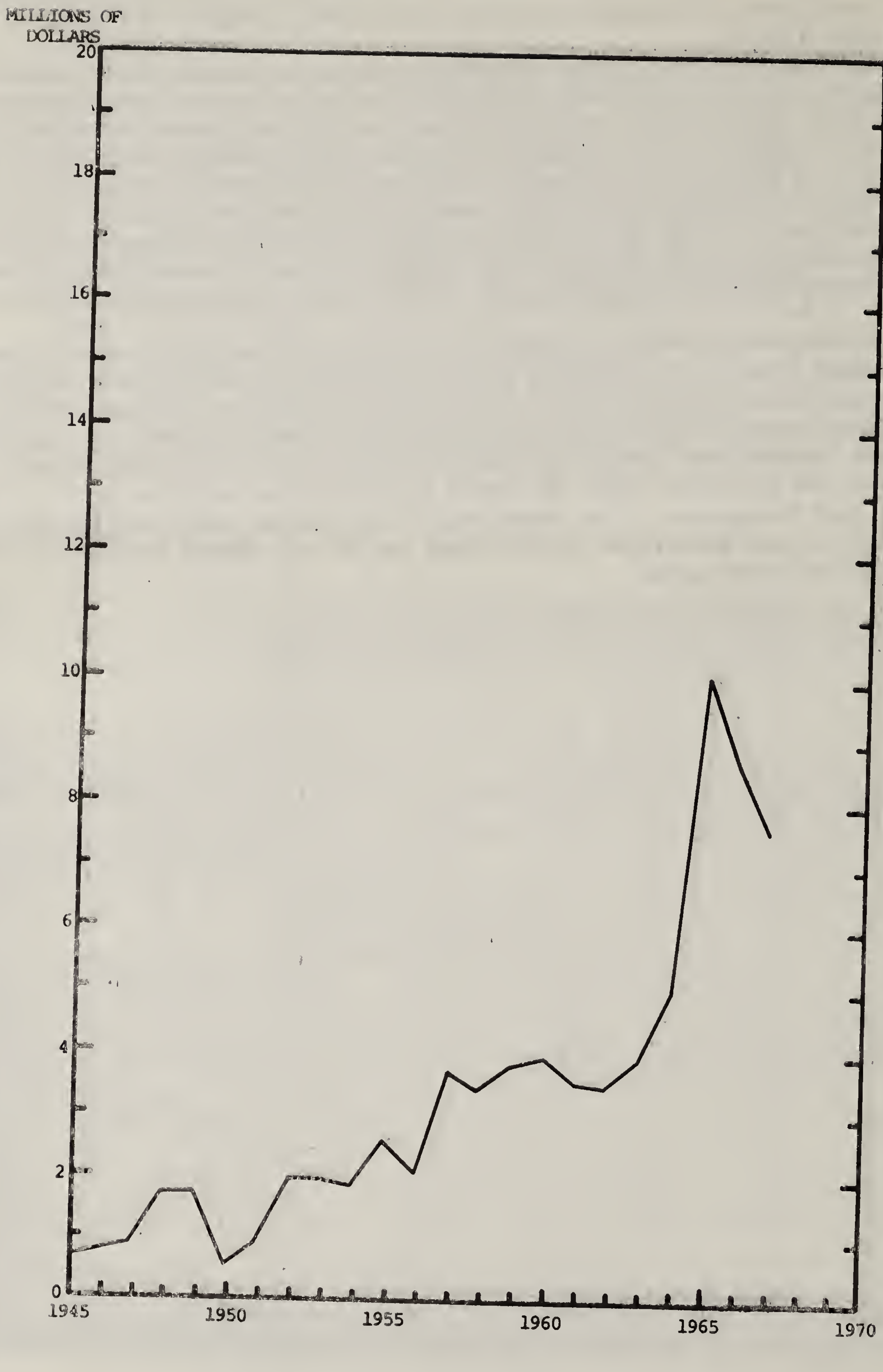


Figure 91 - Value of phosphate minerals produced on the public lands. Source of data: Tables in Appendix F.

B. MINERAL RESOURCES PRODUCED FROM THE PUBLIC LANDS

1. Major Industrial Minerals

Accurate data regarding the value of minerals produced from the public lands of the United States are extremely sparse and are restricted almost entirely to those minerals which come under the Leasing Act of 1920 and the Commodities Disposal Act of 1947. There are no specific figures for either the volumes or values of production from the public lands of any minerals which come under the Mining Act of 1872. Even the data on the so-called leasable minerals are incomplete. In fact, the only nonfuel minerals for which data are readily available are phosphates, potash, sodium minerals, and silica.

The value of phosphate production from public lands in the public domain states of the United States has increased substantially since 1947. Shortly after the close of World War II the total value of phosphate production from the public lands of the United States was valued at approximately one million dollars per year. By the late 1940's this had risen to nearly two million dollars, but subsequently declined to a low of about half a million dollars in 1950. After the start of the Korean War, the rise in the value of phosphates produced on the public lands rose rather steadily, reaching a relative plateau at about four million dollars in the late 1950's and early 1960's. In 1963, phosphate production from public lands began to increase sharply, however, rising to approximately five million dollars in 1964 and to more than 10 million dollars in 1965. Since 1965, however, the value of such output from the public lands has dropped to less than eight million dollars per year. This is still well above the level for 1964, however.

Potash production from the public lands of the United States has not followed a pattern quite as erratic as that followed by phosphate production. After the end of World War II, the value of potassium minerals production from the public lands amounted to about 26 million dollars annually. This rose steadily throughout the late 1940's and well into the mid-1950's, reaching 60 million dollars per year in 1954. There was a slight decline in 1957 to about 55 million dollars, but this was followed by an extremely sharp increase during the late 1950's and early 1960's. By 1959 the value of potassium minerals produced from the public lands of the United States had reached nearly 80 million dollars. By 1964 the output of potassium minerals on the public lands reached a peak of almost 110 million dollars. This peak held for the following year, but after 1965 potash production from the public lands declined rather sharply, sinking to less than 70 million dollars in 1967.

Unlike the value of both phosphates and potash production from public lands in the United States, the value of sodium mineral production from the public lands has not declined within the last several years. Its increase since the end of World War II has been equally dramatic, however. In 1947 the total value of sodium mineral production from the nation's public lands was about five million dollars. This rose rather rapidly during the late 1940's, reaching about 12 million dollars in 1948. By 1950, the total exceeded 15 million dollars. Throughout the 1950's, the value of sodium mineral production from public lands rose substantially, reaching a high in 1960 of more than 26 million dollars. Although this was followed by a slight decline in the succeeding two years, in 1963 sodium mineral production again rose sharply, to approximately 36 million dollars. The total value of sodium production from public lands has remained relatively steady at more than 35 million dollars per year since 1963.

Data available for the value of silica and silica sands produced from the public lands of the United States show a rather substantial increase within the last decade. It may be, however, that this increase is more of a statistical reporting phenomenon than an actual increase in such mineral production.

From the end of World War II until 1958, the total value of silica and silica sands produced from the public lands of the United States was less than one million dollars per year. By 1959 there was a sharp increase in such production to approximately three million dollars. The following year, however, production from the public lands of silica and silica

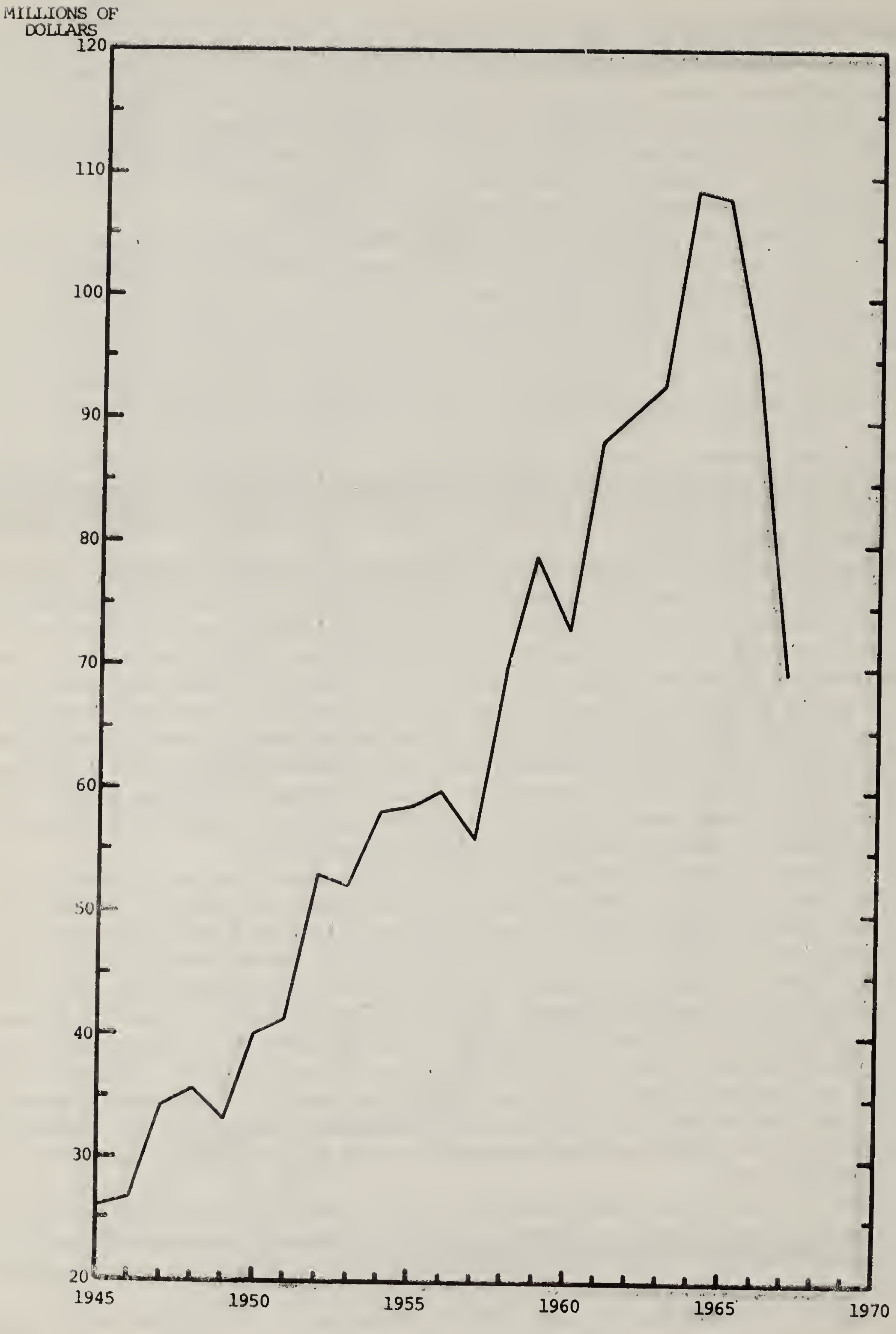


Figure 92 - Value of potassium minerals produced on the public lands. Source of data: Tables in Appendix F.

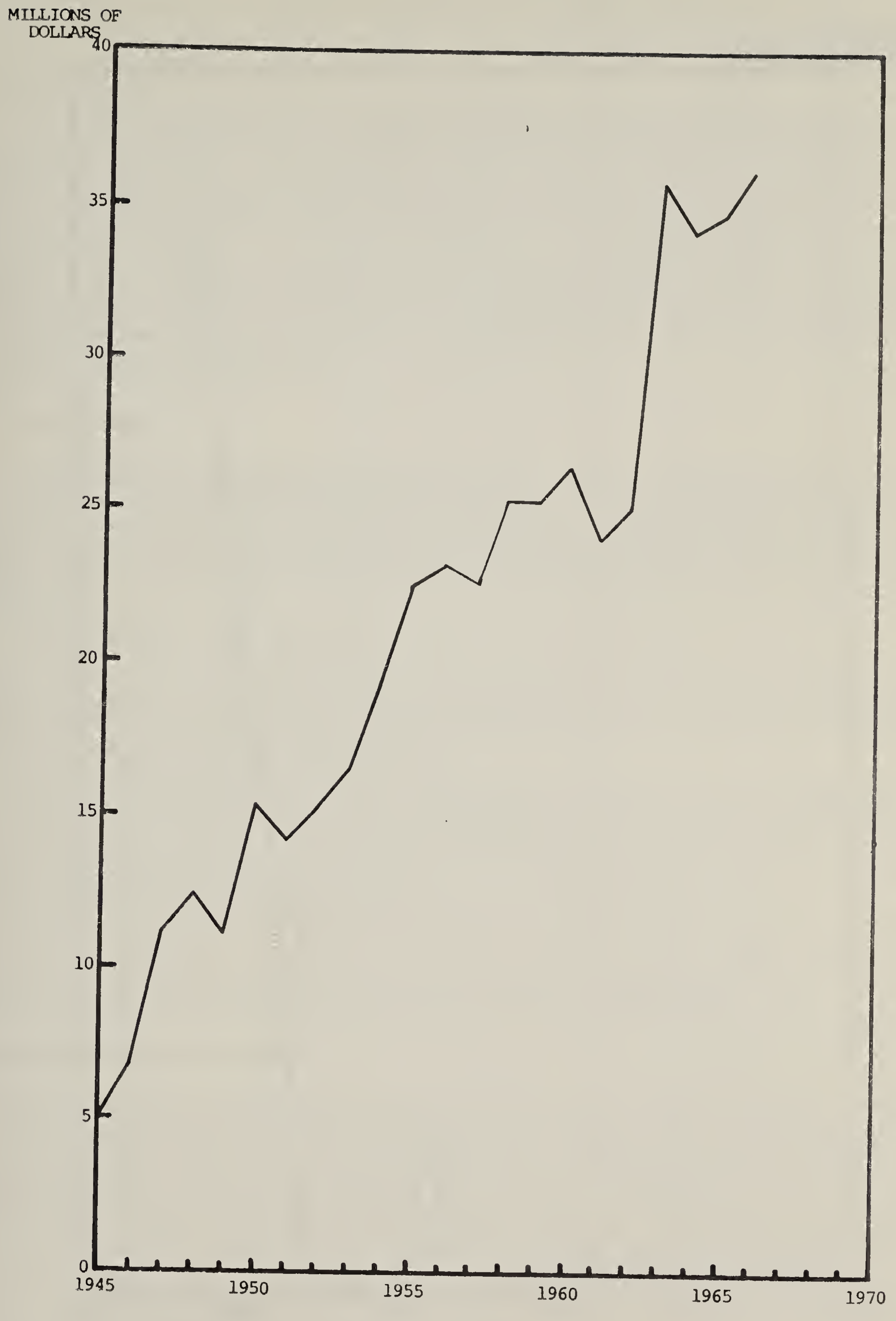


Figure 93 - Value of sodium minerals produced on the public lands.
Source of data: Tables in Appendix F.

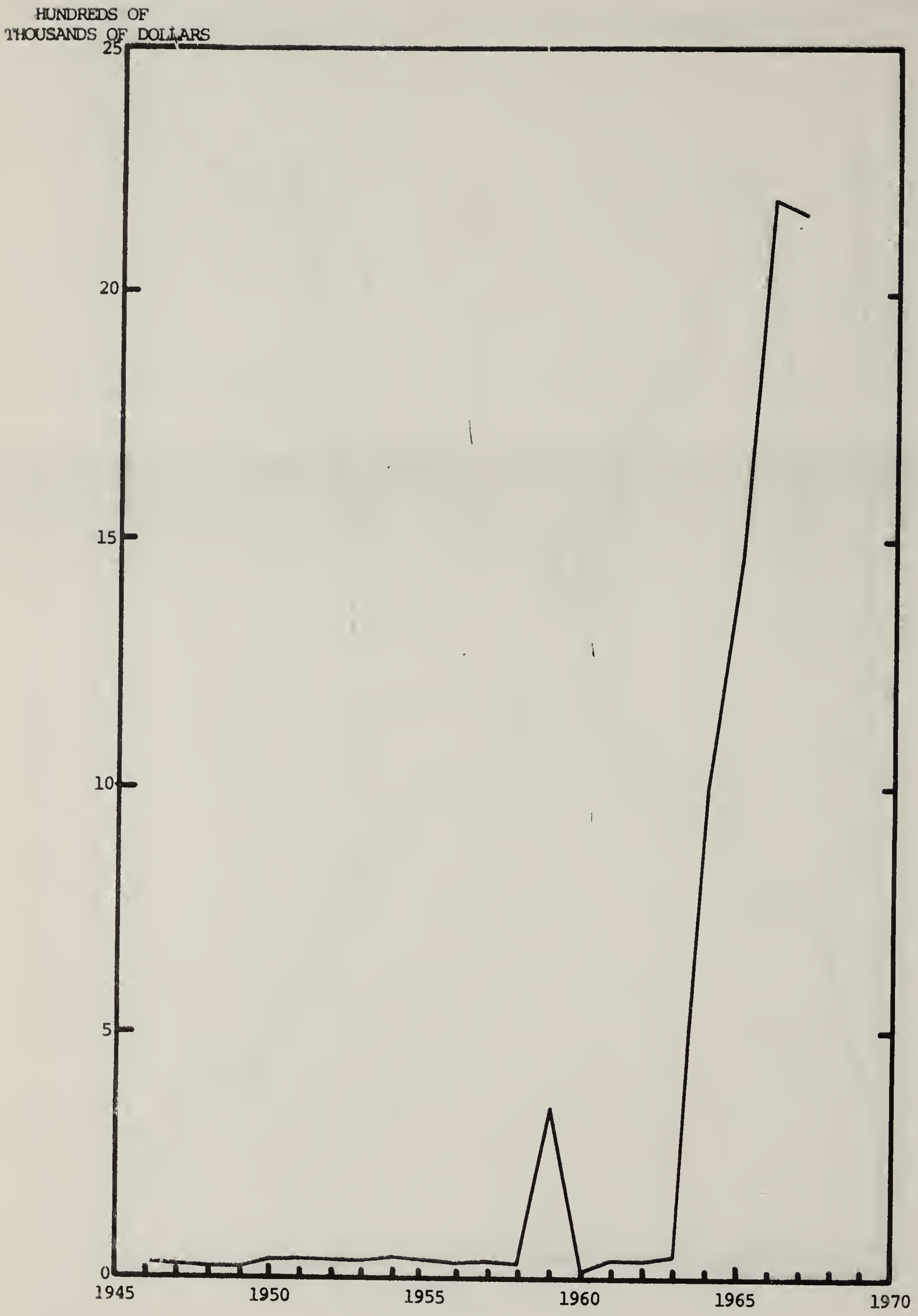


Figure 94 - Value of silica and silica sands produced on the public lands. Source of data: Tables in Appendix F.

sands again dropped to less than one million dollars, where it remained until 1963. In 1964 there was a sharp rise in the value of these industrial minerals on the public lands of the United States. In that year, the tota value of such production exceeded 10 million dollars. The following year (in 1965) the value of silica and silica sand output reached a high of about 22 million dollars. Although there was a slight decline the following year, the total production of silica and silica sand from the public lands has remained about 22 million dollars per year.

It is highly probable that this dramatic increase in the early 1960's in the value of silica and silica sands produced from the public lands of the United States is a reflection of more accurate record keeping than an actual increase in production. There is little doubt that the sharp increases of 10 million dollars each per year in 1964 and 1965 represent better records and the inclusion of large amounts of production in the federal statistics that were not included prior to 1964, rather than substantial increases in actual silica and silica sands output. It is also highly probable that other amounts of silica and silica sands presently being produced from the public lands are not included even in the existing statistics and that the total value of such production from the public lands is in excess of the 20 million dollar valuation currently attached to it.

2. Other Minerals

Other mineral commodities are being and have been produced from the public lands, and the records of such production have been considerably more specific in recent years than in the 1940's and 1950's. Nevertheless, adequate data on such output exist only for public lands that have been acquired by the federal government and for national forest lands. Information on production from privately held mineral claims on public domain is not available.

Nonfuel mineral production from acquired public lands has been slight. In 1967, such output totalled less than 70,000 tons. The greatest share of this came from lead deposits in Missouri and from quartzite and feldspar deposits in Virginia and Georgia. The only nonfuel mineral output from acquired public land in the Western States in 1967 was less than 400 tons of uranium ore mined in New Mexico.[167]

The sale of mineral commodities from the public lands under the Materials Disposal Act of 1947 has also been slight. In 1967 the total value of such sales was little more than $113,000. All but $100 of this was in the 11 Western States. Except for limited amounts of top soil and soil additives as well as 250 tons of "industrial minerals," all of the minerals so produced were construction materials.[168]

The estimated value of minerals produced from the public lands under free-use permits has been much greater, exceeding two million dollars in 1967. Again, except for an estimated $36,000 worth of topsoil, all of these mineral commodities were construction materials, and all were produced in the Western States and Alaska.[169]

3. Locatable Minerals Production

Despite the fact that existing records do not show sizeable amounts of mineral production from public lands, there are substantial tonnages of *locatable* minerals being produced. Public lands have in the past and still form an important segment of the mineral resources produced by the nation's private mining firms. As shown by Table 25, about half of the mineral lands in production today were acquired on the public domain. Nearly three-fourths of these were directly acquired under the mineral location system. An additional ten percent of all active mineral lands were originally acquired under the mining location laws but subsequently passed to private ownership before being acquired by the present minerals producer.

Because of the importance of public lands in the present production of nonfuel minerals, as well as their high geologic potential for the development of future mineral

Table 25

THE IMPORTANCE OF FEDERAL LAND IN UNITED STATES MINERAL RESOURCES DEVELOPMENT
1968

Means by which Active Mining Firms Have Acquired Presently Used Mineral Lands	Total Sample Acreage	Percent of Acreage	Number of Sample Firms	Percent of Firms[a]
Direct location of federal land	88,633	30.5	28	36
Purchase of unpatented claims	23,996	8.3	14	18
Leases on federal land	34,340	11.8	6	8
SUB-TOTAL, FEDERAL LAND	146,969	50.6	48	62
Leases on Indian lands	1,315	0.4	2	3
Leases on state lands	22,873	7.9	13	17
SUB-TOTAL, NON-PRIVATE	171,157	58.9	63	81
Leases on private lands	28,984	10.0	23	29
Leases with options to buy on private land	5,066	1.7	9	12
Purchase of patented mining claims	30,716	10.6	21	27
Acquisition by merger	29,349	10.1	6	8
Other means[b]	25,146	8.7	22	28
SAMPLE TOTAL	290,418	100.0	144	

[a] Based on a total sample response of 78. Some firms have acquired land by more than one means.

[b] Mostly outright purchase of privately owned land plus some land exchanges.

Source of Data: Survey of both large and small active mineral producers in the United States conducted by the Division of Economic and Business Research, The University of Arizona.

deposits, it is surprising to note that the number of mineral patent applications has declined sharply since the early 1960's (see Figure 95). Prior to 1961, the number of mineral patent applications had been rising, as had the nation's mineral output. Total nonfuel mineral production continued to rise after 1961 despite the drop in new mineral patent applications.

Since 1961, the number of mineral patent applications acted upon favorably by the federal government has also declined. As shown in Figure 96, since 1960, there has been a strong positive relationship between the number of mineral patent applications and the number of applications approved. As shown in Figure 97, however, such was not the case prior to 1960. From 1950 through 1959 there was, in fact, a moderate inverse relationship between the number of mineral patent applications and the number recommended for patent.

Since 1960, the proportion of mineral patent applications recommended for patent has varied between 30 and 60 percent. Since 1963, the proportion of applications acted upon favorably appears to have followed a rising trend, although even in more recent years nearly half of all mineral patent applications have been rejected.

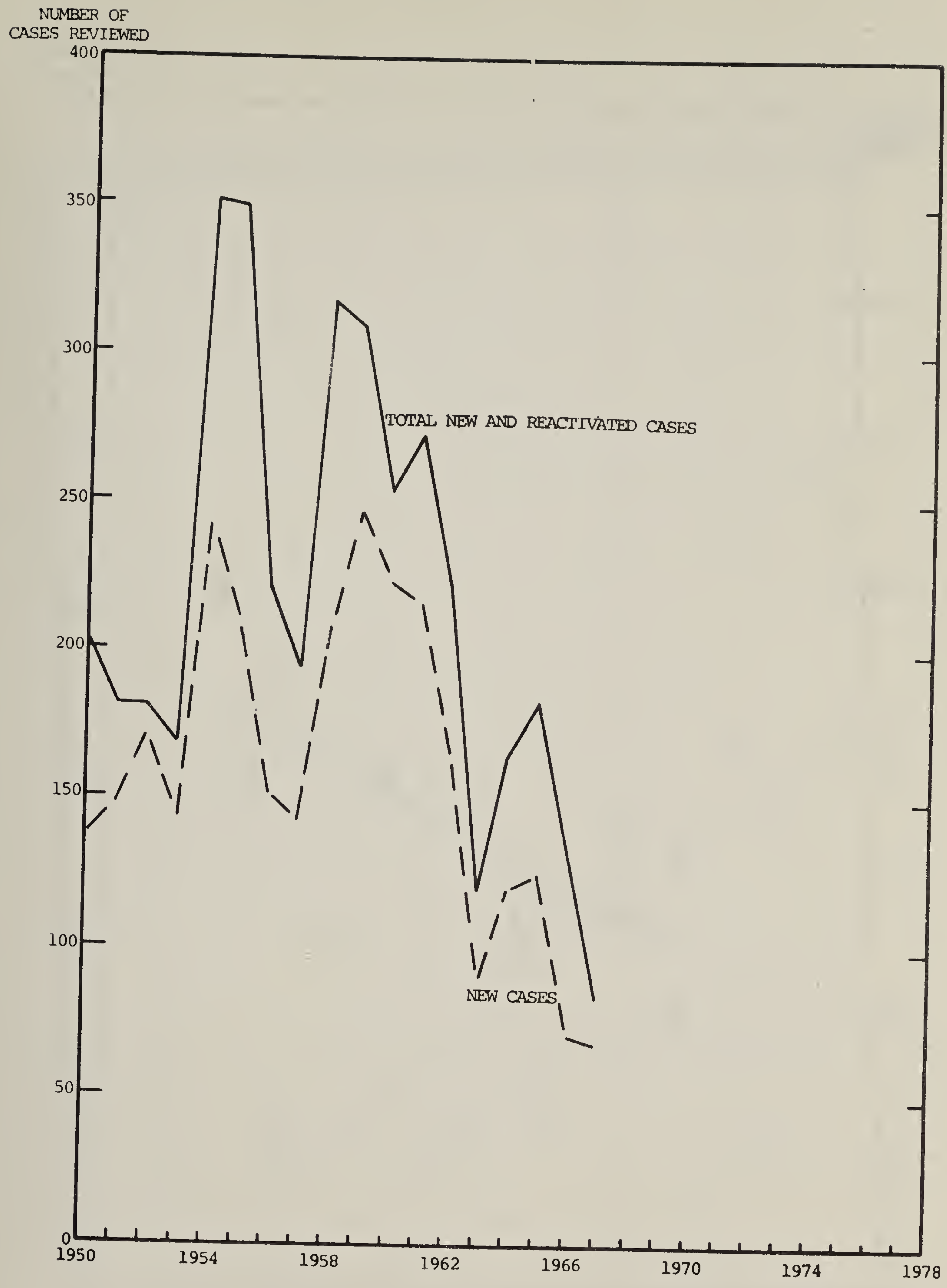


Fig. 95 - Mineral Patent Applications, Cases for Review

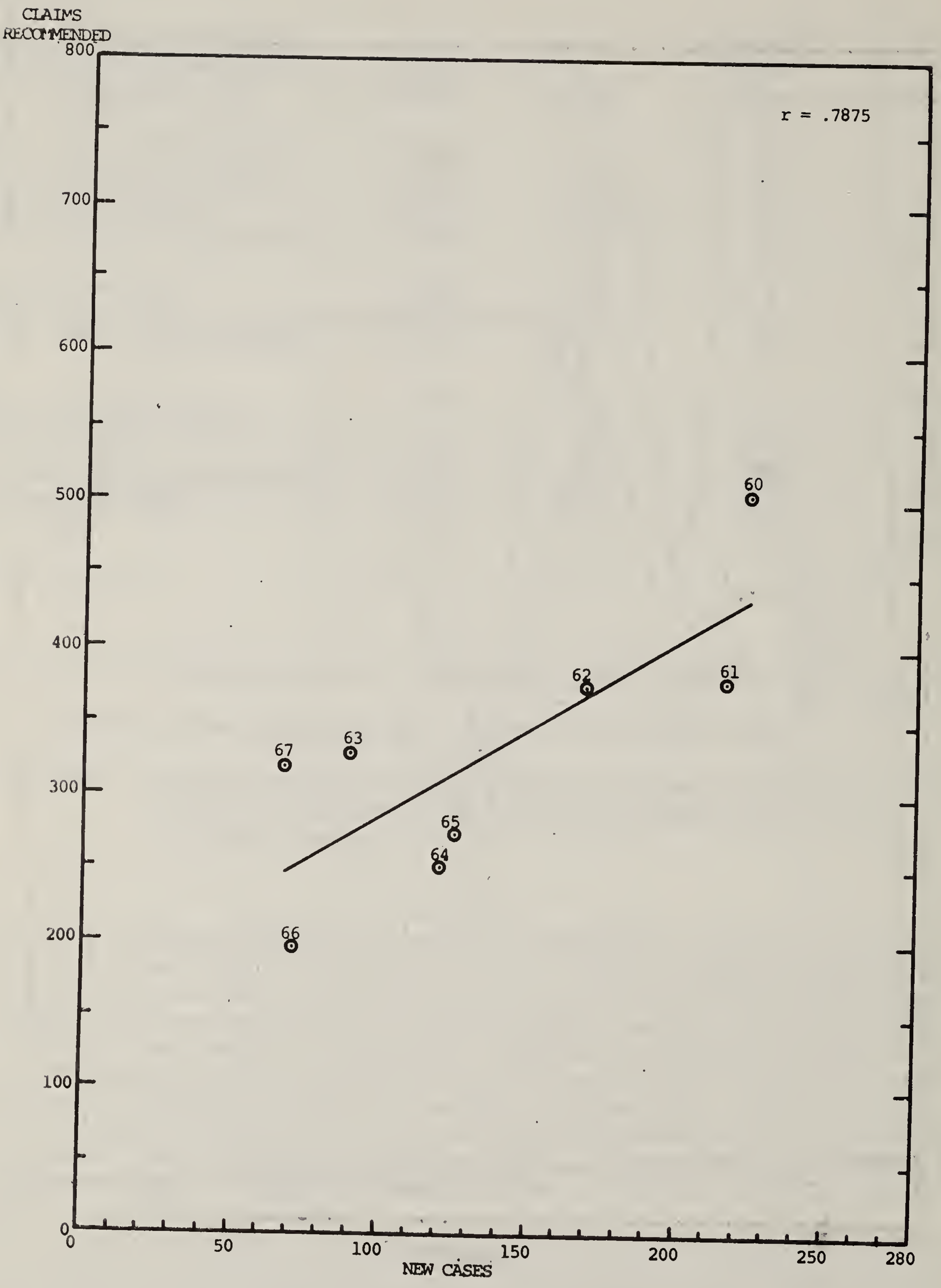


Fig. 96 - Mineral Patent Applications vs. Recommendations for Patent

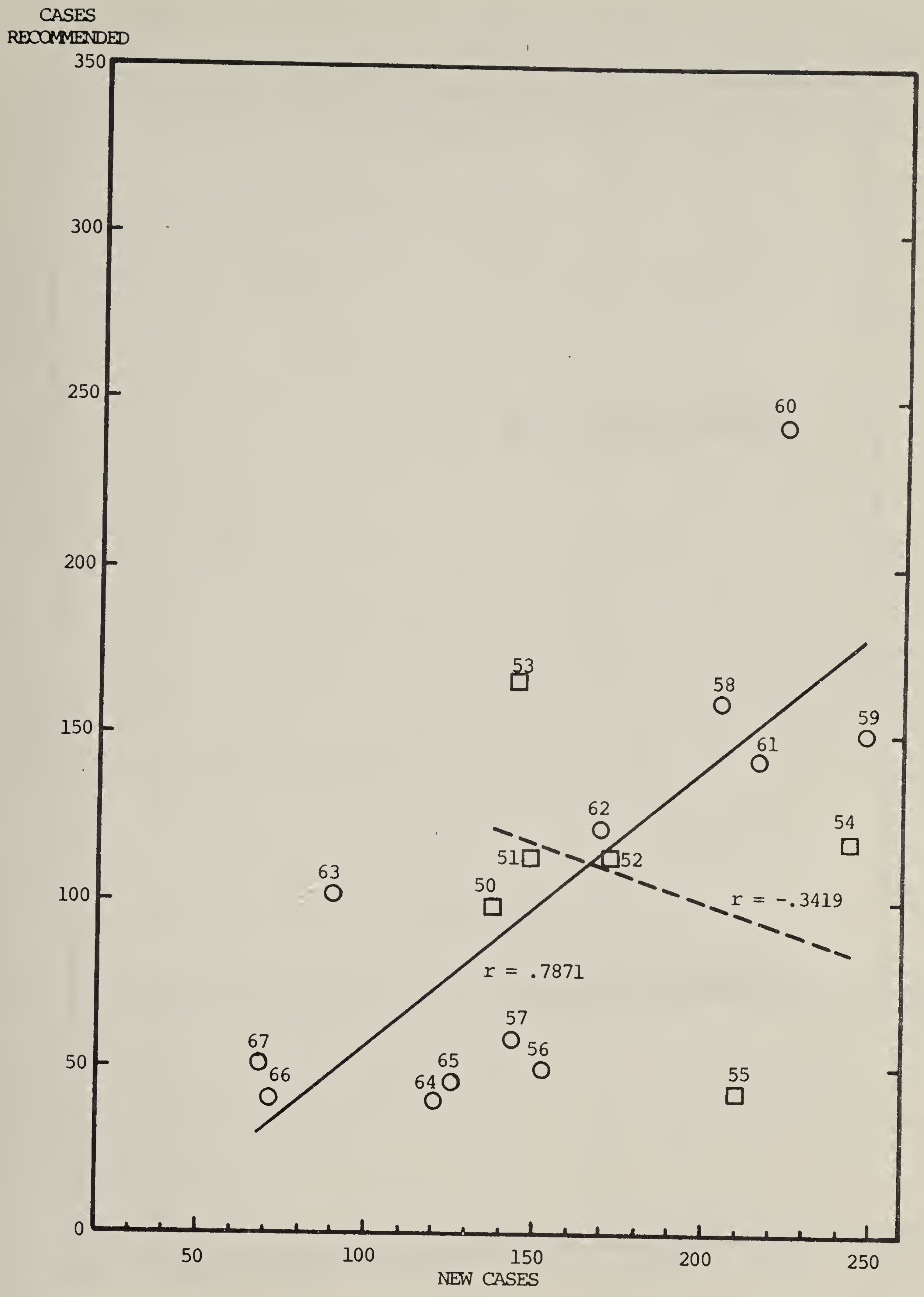


Fig. 97 - New cases received vs. cases recommended for patent. The dashed line represents the average relationship from 1950 to 1955. The solid line represents the average relationship since 1955.

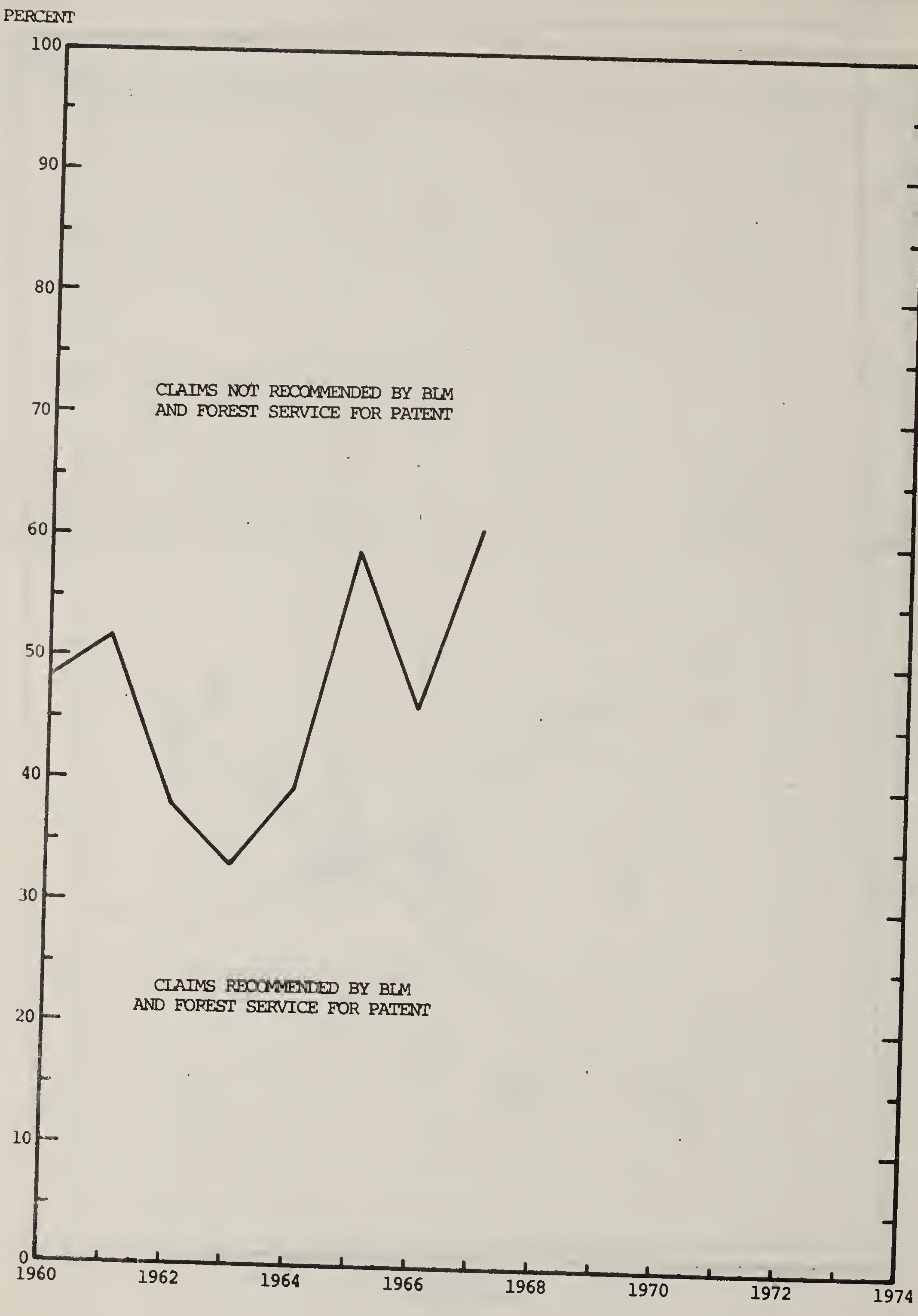


Fig. 98 - Proportion of Mineral Patent Applications Recommended for Patent

C. MINERALS RESERVED TO THE UNITED STATES

For the most part, the extent of surface area in the Western United States that is still under the control of the federal government does not provide an adequate measure of the total mineral resources still owned by the United States. In some areas, although the surface is under federal ownership, the minerals are held by private interests by means of valid but unpatented mining claims. While the full area covered by valid but unpatented mining claims is impossible to determine, it is undoubtedly far less than the area in which the mineral rights are controlled by the federal government but with the surface under non-federal ownership.

These lands, where mineral rights have been severed from the surface and reserved to the federal government, cover vast areas of the Western States, even in regions of substantial private land ownership and urban and agricultural development. In some of these areas, the rights to all minerals have been reserved to the federal government, while in others only specific minerals have been so reserved. In many areas, the reservation of all leaseable minerals, both fuel and nonfuel, is common. In other areas, more specific reservations, particularly for oil and gas, sodium minerals, and uranium, are prevalent.

The nature and extent of the areas in which mineral rights have been severed from surface rights and reserved to the federal government vary from region to region and from state to state. The following maps (Figures 99 through 109) provide a detailed picture of the situation in each state. In some states, those areas with reserved minerals have been subject to specific mineral reservations and thus also have other minerals that are not reserved. In many states, large areas are indicated as having few reserved minerals simply because the surface land in those areas is still owned by the federal government.

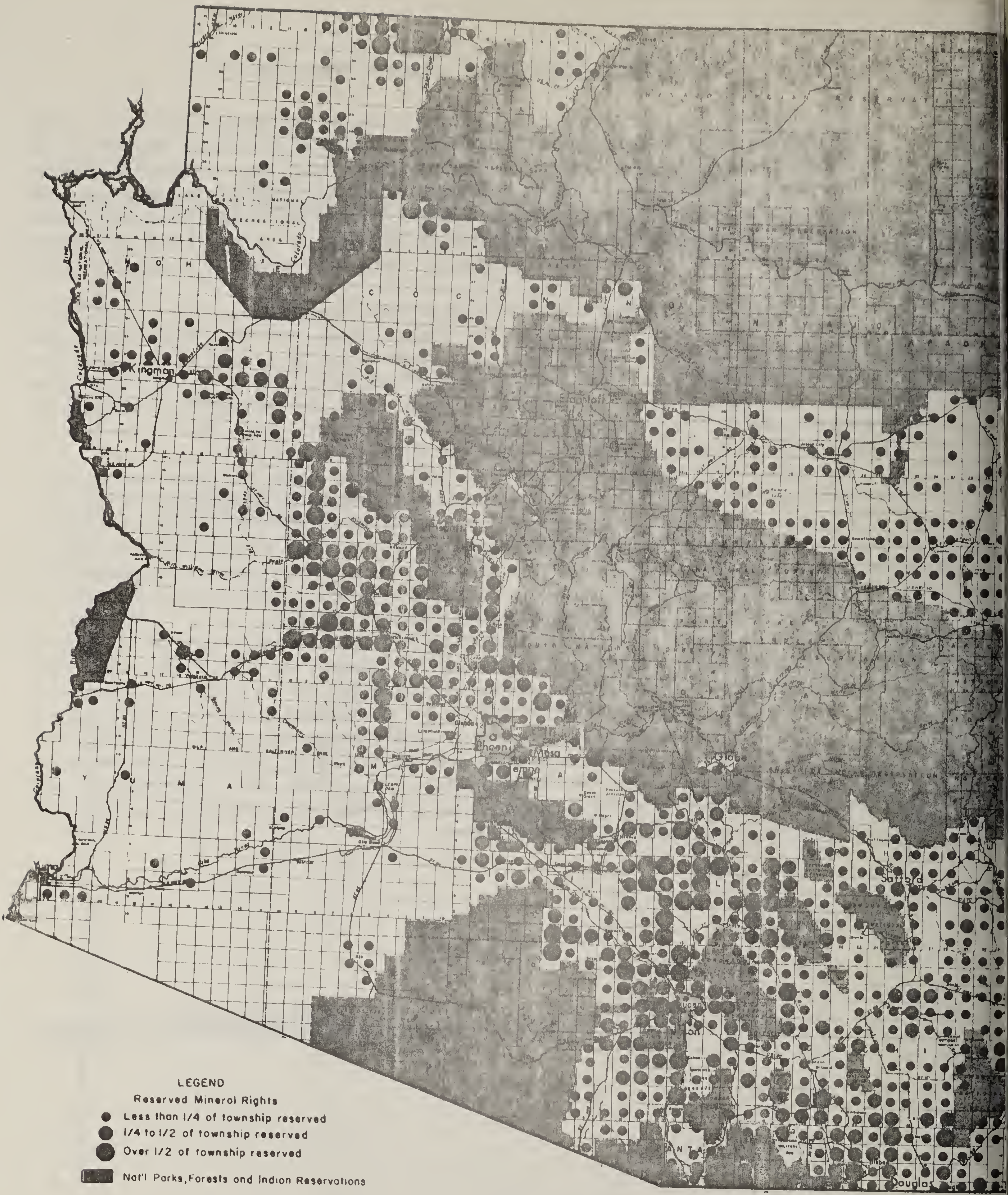
With the total area of known and potential mineral resources owned by the federal government even more extensive than the surface land area so held, future public land policy is likely to be of far greater importance to minerals users than to any other single class of user of the public land. Many of the reserved minerals lands, however, are in areas in which the surface is now devoted to other uses. These other uses became prevalent generally because no valuable mineral deposits were close enough to the surface of the land to be apparent to its early users. The development of technology for the detection and utilization of minerals at depth, however, greatly increases the potential of such lands as future sources of valuable mineral commodities.

FOOTNOTES

168/ *Public Land Statistics*, Bureau of Land Management, U.S. Department of the Interior (1967), p. 85.

169/ *Ibid.*, p. 92.

170/ *Ibid.*, p. 93.


LEGEND
Reserved Mineral Rights
● Less than 1/4 of township reserved
● 1/4 to 1/2 of township reserved
● Over 1/2 of township reserved
▨ Nat'l Parks, Forests and Indian Reservations
0 5 10 20 30 40 Miles
Kingman
Flagstaff
Phoenix
Mesa
Tempe
Globe
Safford
Tucson
Douglas
Colorado
NAVAJO INDIAN RESERVATION
HOPI INDIAN RESERVATION
LAKE MEAD NATIONAL RECREATIONAL AREA
MOHAVE
COCONINO
NAVAJO
APACHE
YUMA
MARICOPA
PINAL
GRAHAM
COCHISE
SANTA CRUZ

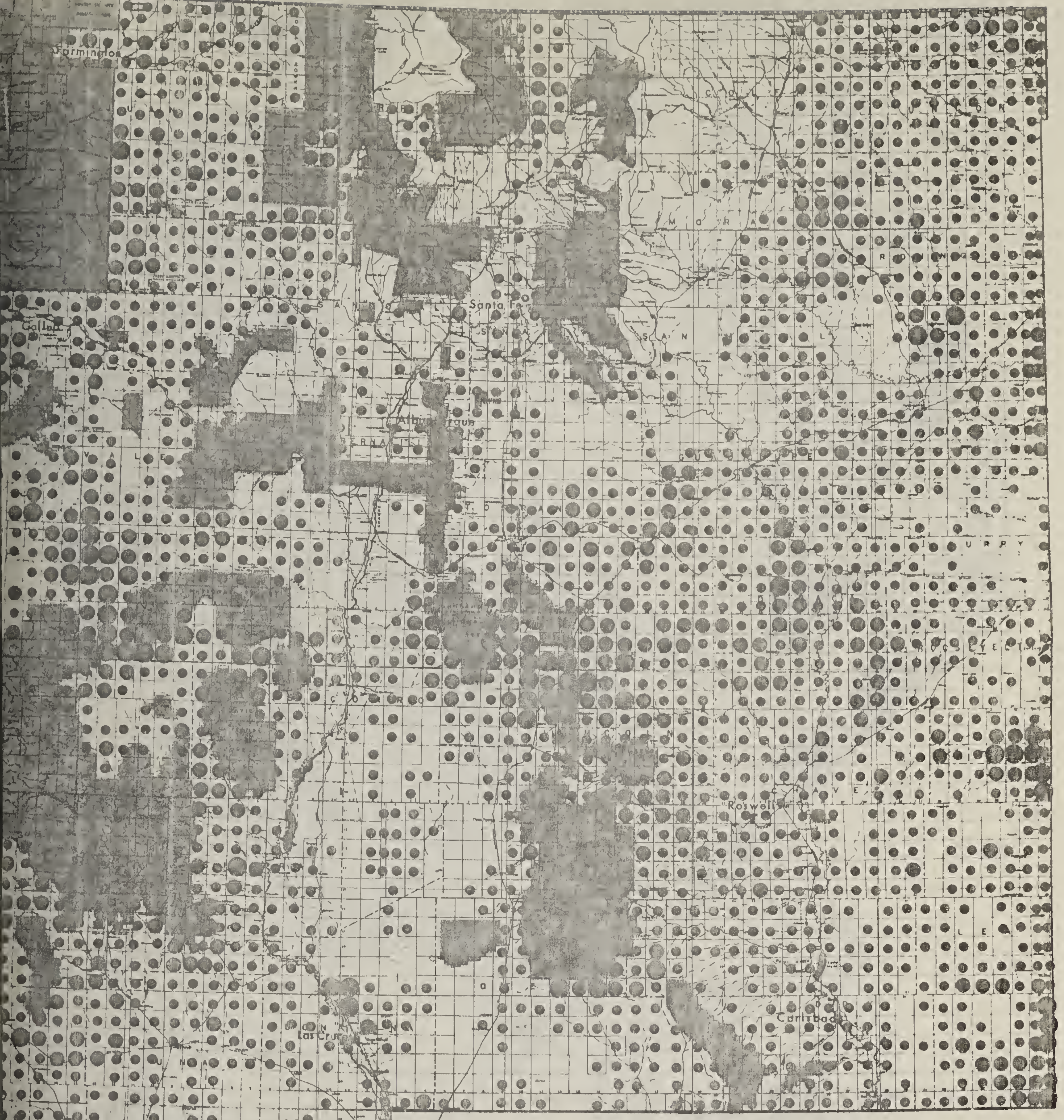
EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMEN

ARIZONA, 1968

Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Von Duyn

Rights to oil or some minerals severed from surface rights and reserved to the federal government.

Fig. 99 - Areas of Arizona where the surface ownership has passed from the federal government but where ownership of the minerals has been retained. Throughout most of the state, rights to all minerals are still owned by the federal government.



EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
NEW MEXICO, 1968

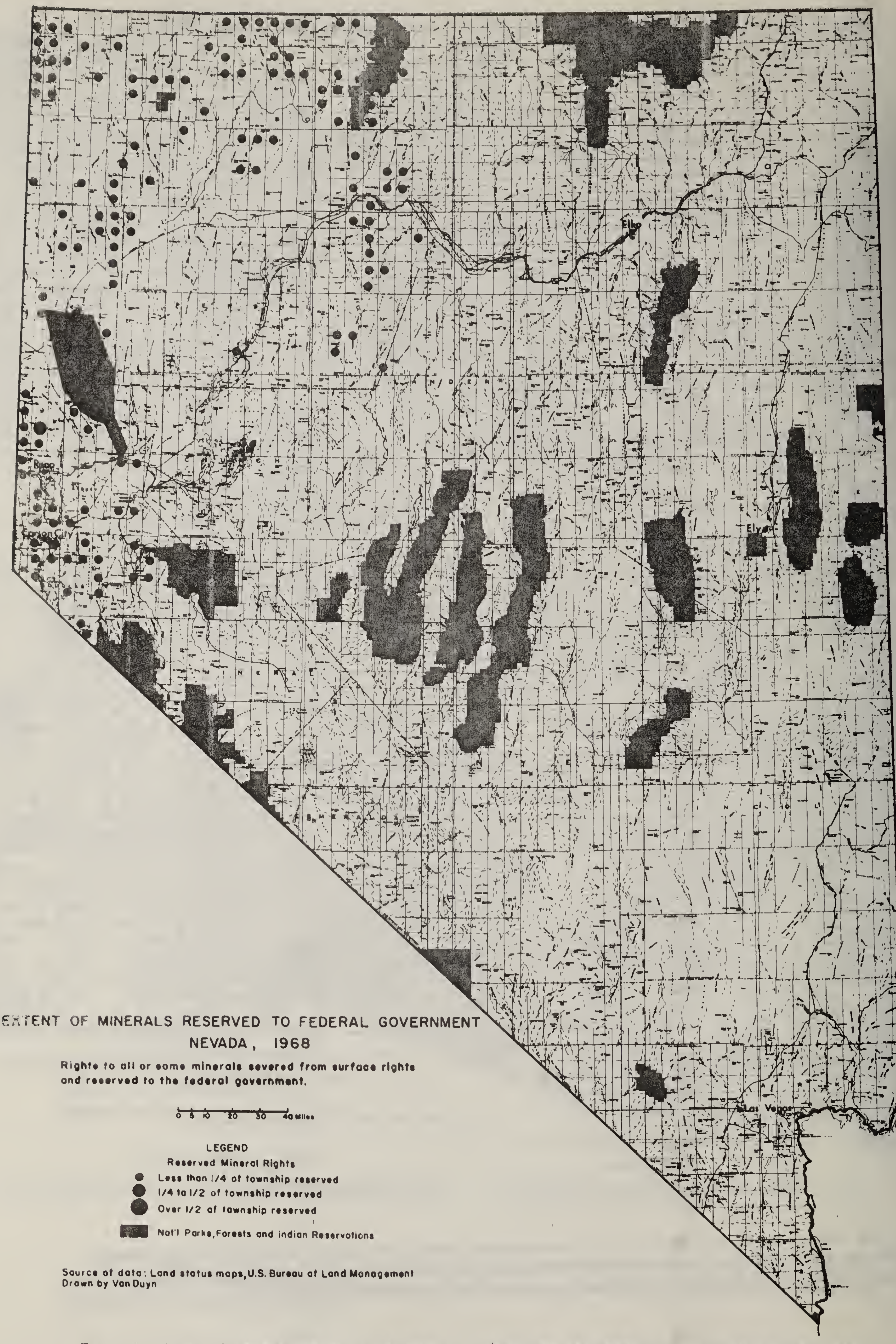
Rights to oil or some minerals severed from surface rights and reserved to the federal government.

0 5 10 20 30 40 Miles

LEGEND
Reserved Mineral Rights
- ● Less than 1/4 of township reserved
- ● 1/4 to 1/2 of township reserved
- ● Over 1/2 of township reserved
- ▨ Nat'l Forests and Indian Reservations

Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Van Duyn and Weller

Fig. 100 - Areas in New Mexico where the surface has passed from federal ownership but the mineral rights are still owned by the federal government. In most of the eastern part of the state, only the rights to certain minerals (mostly oil, gas, and potash) have been reserved to the federal government.



EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
NEVADA, 1968

Rights to all or some minerals severed from surface rights and reserved to the federal government.

Reno
Carson City
Elko
Ely
Las Vegas
0 5 10 20 30 40 Miles
LEGEND
Reserved Mineral Rights
● Less than 1/4 of township reserved
● 1/4 to 1/2 of township reserved
● Over 1/2 of township reserved
▨ Nat'l Parks, Forests and indian Reservations

Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Van Duyn

Fig. 101 - Areas of Nevada where the ownership of the surface has passed from the federal government but where it still owns the mineral rights. Most of the surface in Nevada is still owned by the federal government.

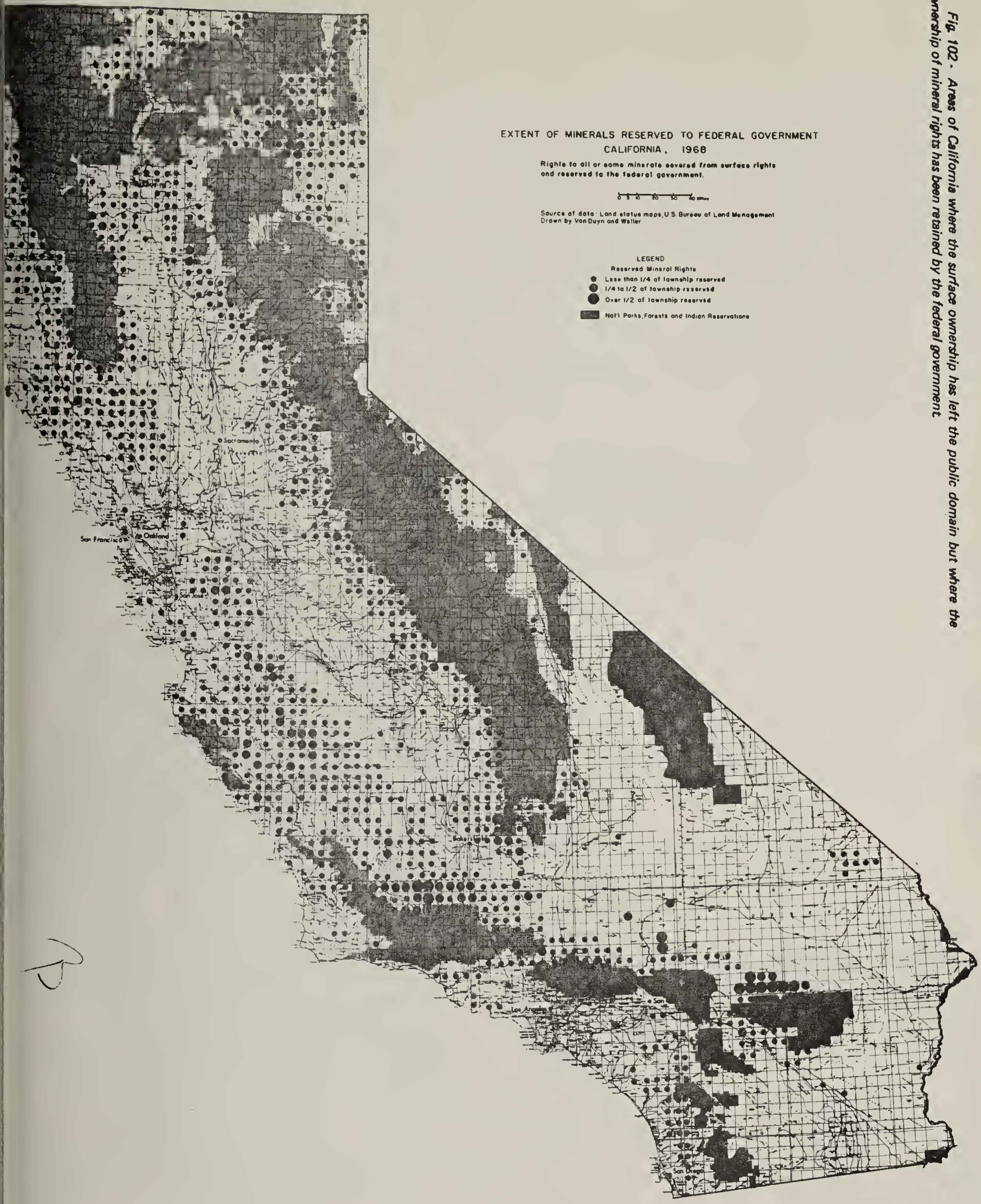
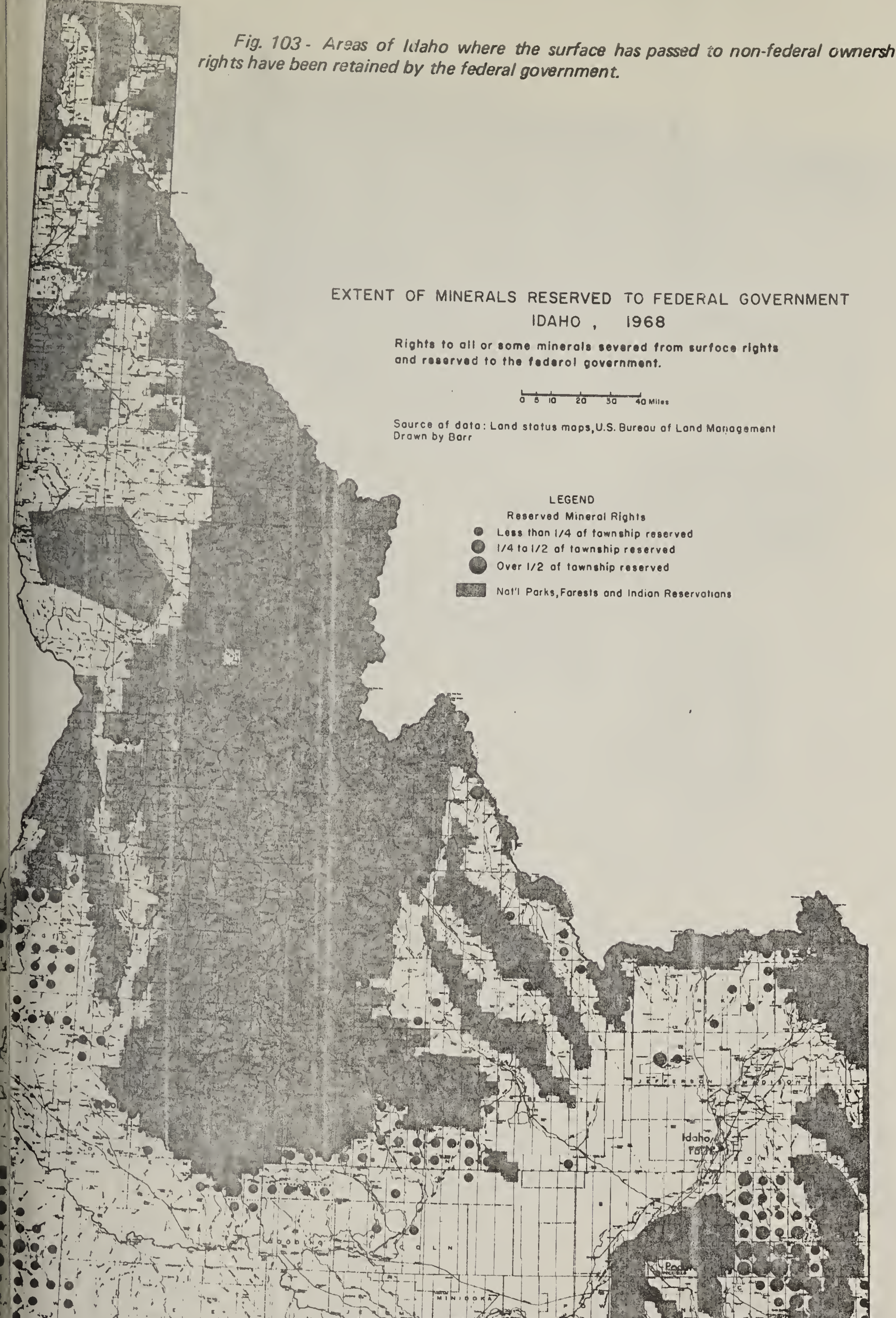

EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
CALIFORNIA, 1968
Rights to all or some minerals severed from surface rights and reserved to the federal government.
0 5 10 20 30 40 Miles
Source of data · Land status maps, U.S. Bureau of Land Management
Drawn by Van Duyn and Weller
LEGEND
Reserved Mineral Rights
● Less than 1/4 of township reserved
● 1/4 to 1/2 of township reserved
● Over 1/2 of township reserved
▨ Nat'l Parks, Forests and Indian Reservations
Sacramento
San Francisco
Oakland
San Jose
Bakersfield
Los Angeles
San
San Diego

Fig. 102. Areas of California where the surface ownership has left the public domain but where the ownership of mineral rights has been retained by the federal government.

Fig. 103 - Areas of Idaho where the surface has passed to non-federal ownership but where mineral rights have been retained by the federal government.


EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
IDAHO, 1968
Rights to all or some minerals severed from surface rights and reserved to the federal government.
0 5 10 20 30 40 Miles
Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Barr
LEGEND
Reserved Mineral Rights
● Less than 1/4 of township reserved
● 1/4 to 1/2 of township reserved
● Over 1/2 of township reserved
▨ Nat'l Parks, Forests and Indian Reservations
JEFFERSON
MADISON
Idaho Falls
GOODING
MINIDOKA

Preceding page blank

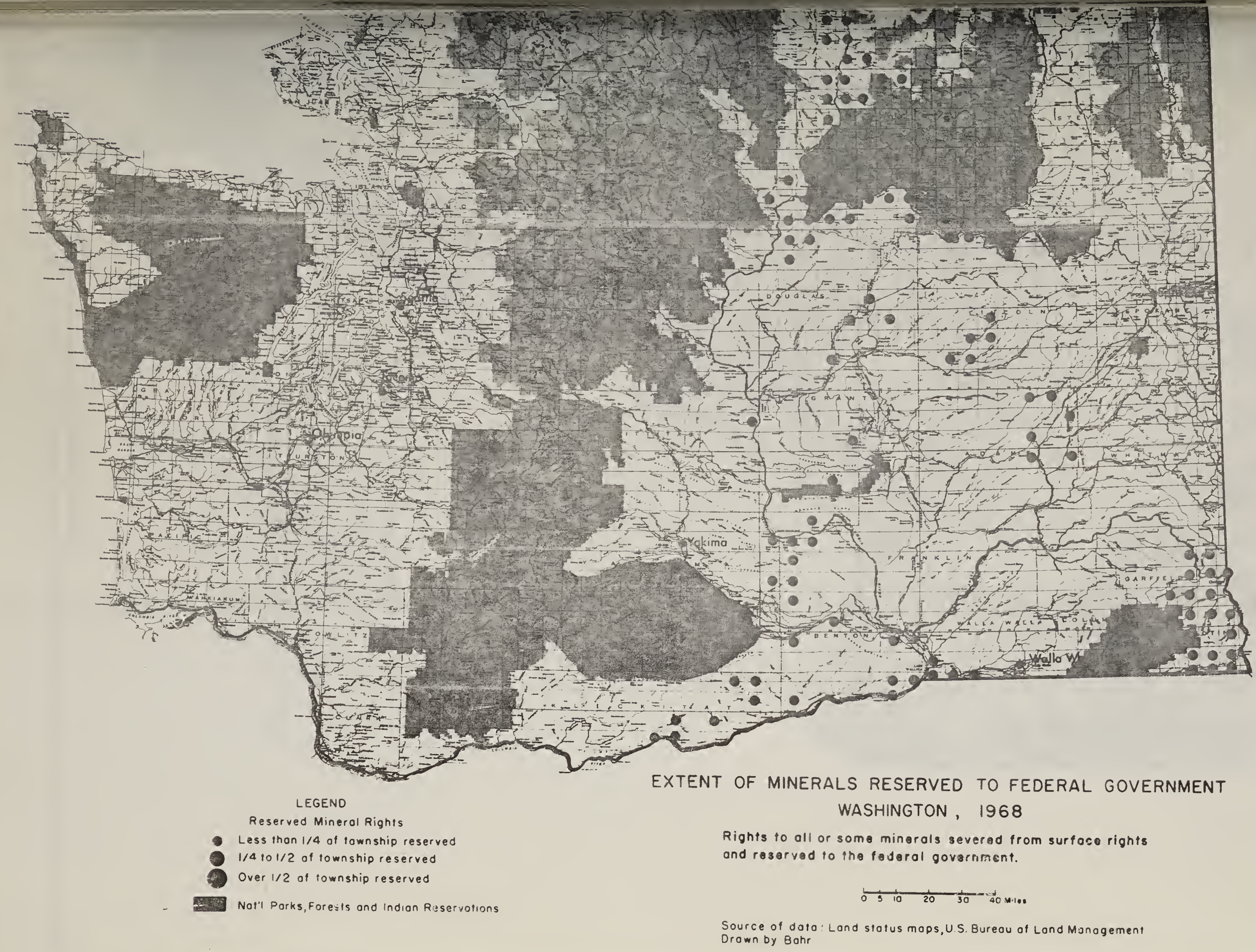
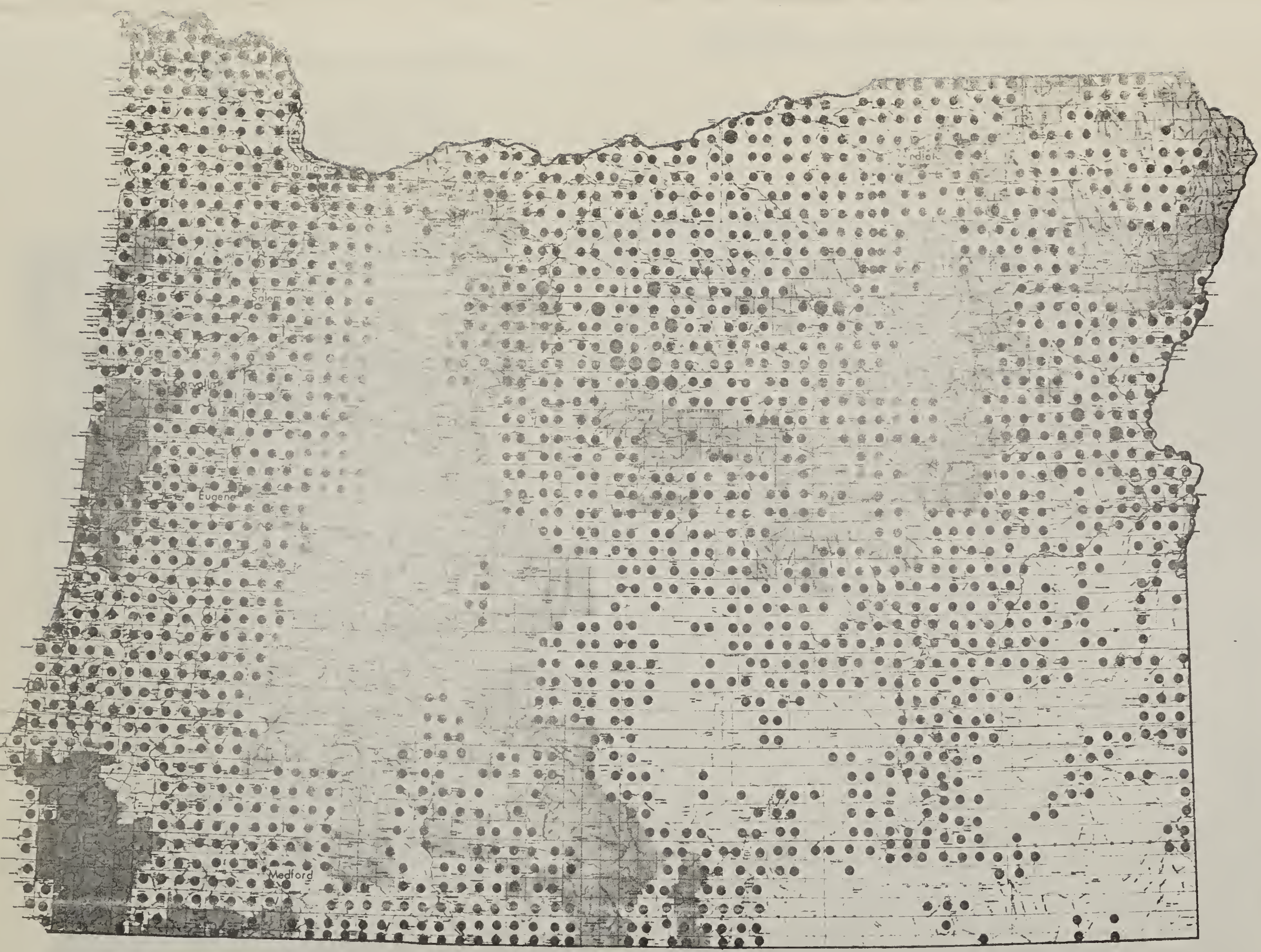

EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
WASHINGTON, 1968
Rights to all or some minerals severed from surface rights and reserved to the federal government.
LEGEND
Reserved Mineral Rights
● Less than 1/4 of township reserved
● 1/4 to 1/2 of township reserved
● Over 1/2 of township reserved
▨ Nat'l Parks, Forests and Indian Reservations
0 5 10 20 30 40 Miles
Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Bahr
Seattle
Olympia
Yakima
Walla W
DOUGLAS
GRANT
FRANKLIN
BENTON
WALLA WALLA
GARFIELD
LINCOLN
SPOKANE
WHITMAN
THURSTON
WAHKIAKUM
COWLITZ
KLICKITAT
CLARK
MASON
GRAYS HARBOR
PACIFIC
LEWIS
STEVENS
COLUMBIA

Fig. 104 - Areas in Washington where the ownership of the mineral rights has been reserved to the federal government even though the surface has left the public domain. Virtually all severed rights areas are in Eastern Washington.



EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
OREGON, 1968

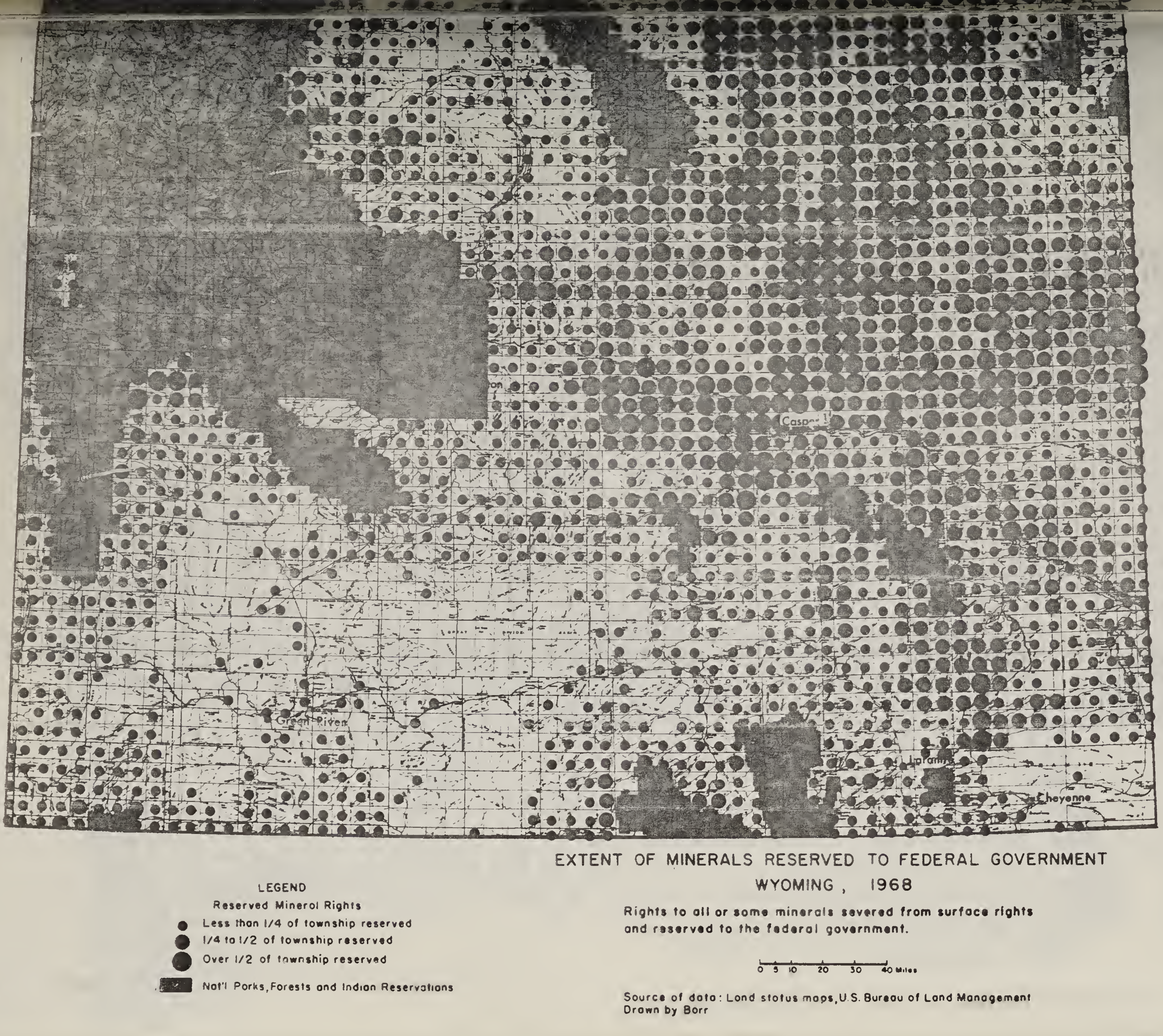
Rights to oil or some minerals severed from surface rights and reserved to the federal government.

LEGEND
Reserved Mineral Rights
- • Less than 1/4 of township reserved
- ● 1/4 to 1/2 of township reserved
- ⬤ Over 1/2 of township reserved
- ▨ Nat'l Parks, Forests and Indian Reservations

0 5 10 20 30 40 Miles

Source of data: Land status maps, U S Bureau of Land Management
Drawn by Von Duyn

Fig. 105 - Areas in Oregon where the ownership of mineral rights has been reserved to the federal government even though the surface has left the public domain. Although such reserved minerals areas are widespread, less than one-fourth of each township has any reserved mineral rights.



EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT

WYOMING , 1968

Rights to all or some minerals severed from surface rights and reserved to the federal government.

LEGEND

Reserved Mineral Rights

● Less than 1/4 of township reserved

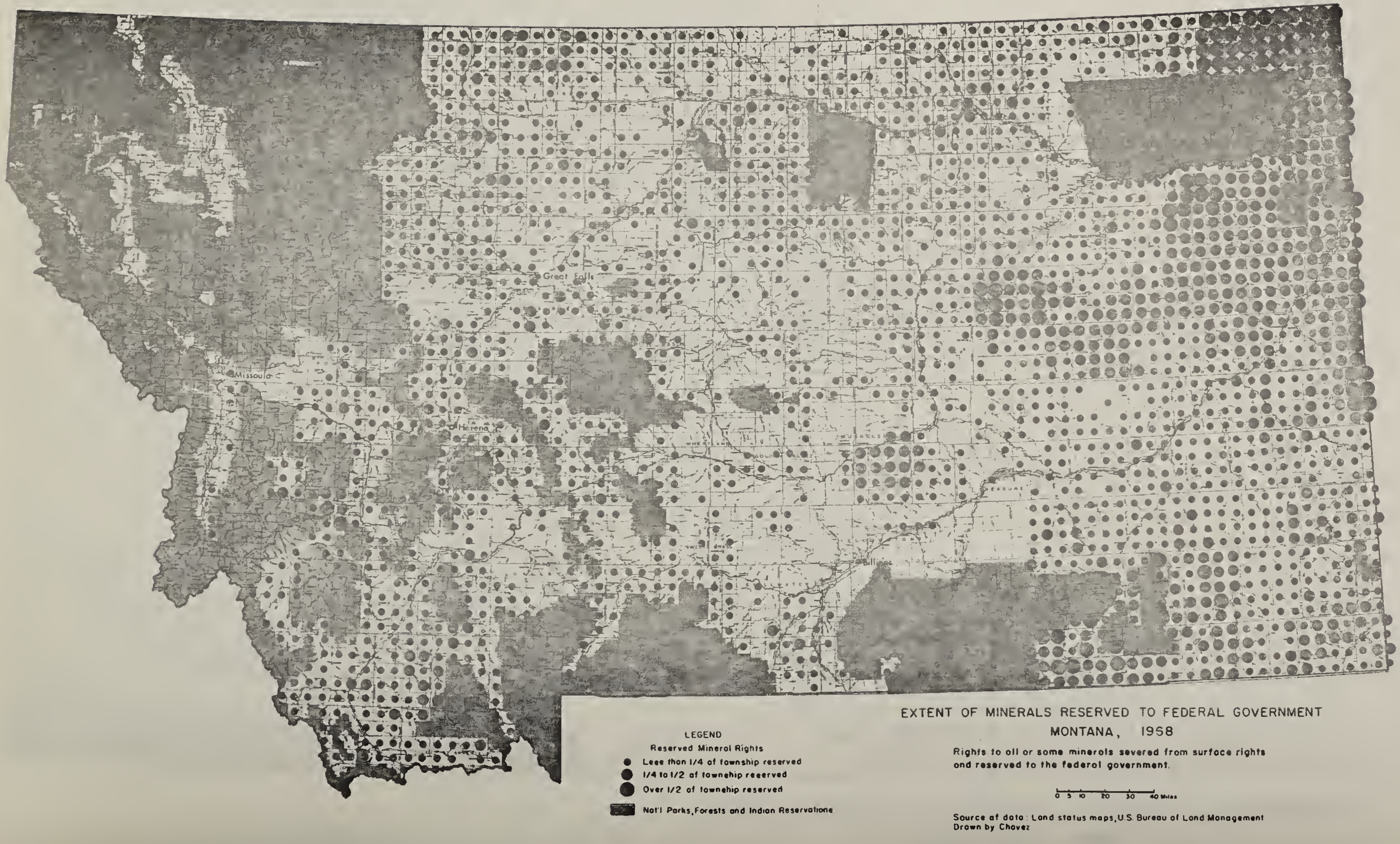
● 1/4 to 1/2 of township reserved

● Over 1/2 of township reserved

▨ Nat'l Parks, Forests and Indian Reservations

Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Barr

Fig. 106 - Areas of Wyoming where, although the surface is no longer under federal jurisdiction, some of the minerals are. Throughout most of the state, only the "leaseable" minerals are reserved to the federal government.



EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
MONTANA, 1958

Rights to all or some minerals severed from surface rights and reserved to the federal government.

LEGEND
Reserved Mineral Rights
- ● Less than 1/4 of township reserved
- ● 1/4 to 1/2 of township reserved
- ● Over 1/2 of township reserved
- ▆ Nat'l Parks, Forests and Indian Reservations

Source of data: Land status maps, U.S. Bureau of Land Management
Drawn by Chavez

Fig. 107 - Areas of Montana where the surface has passed to non-federal ownership but where mineral rights have been retained by the federal government.

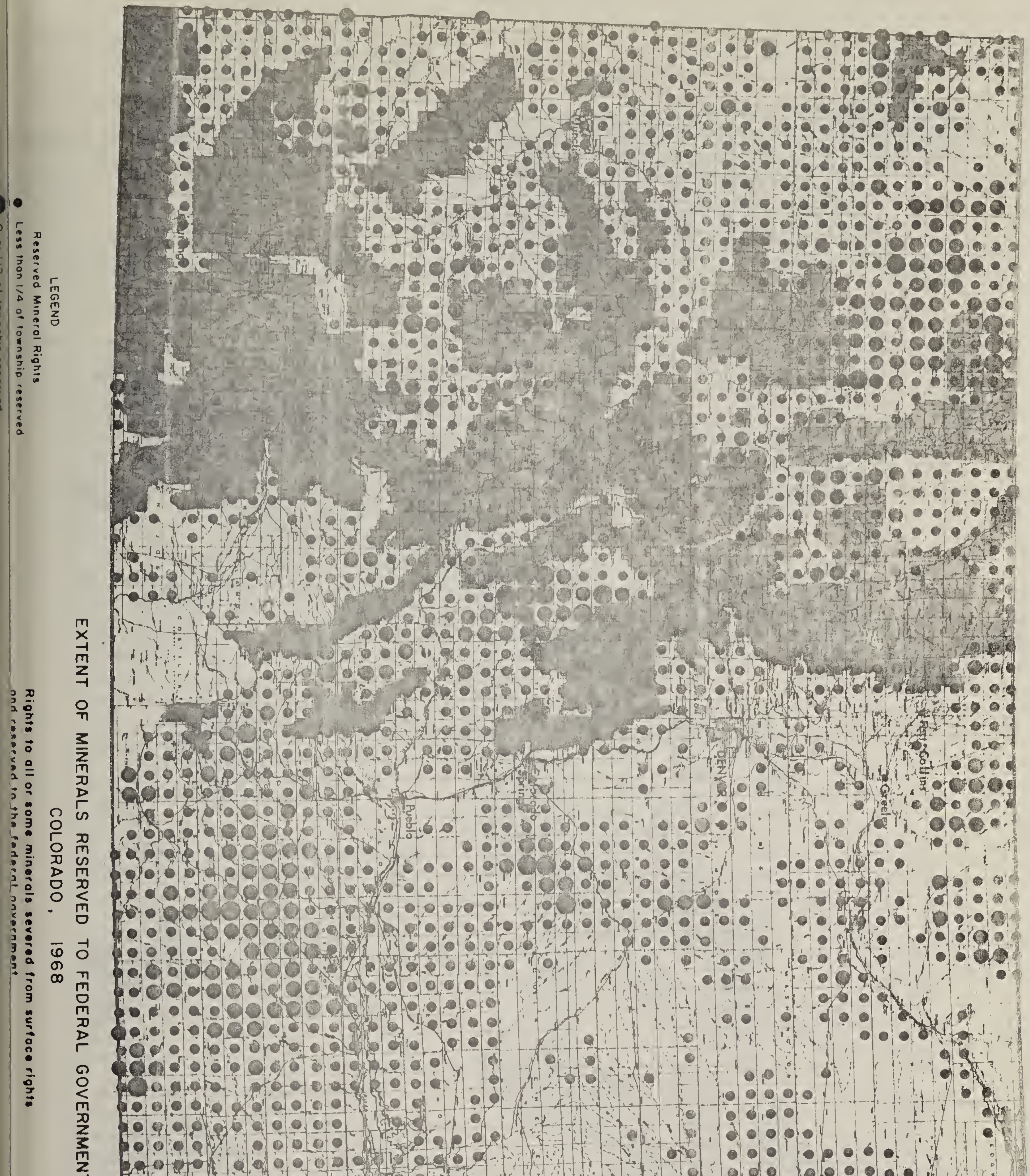

EXTENT OF MINERALS RESERVED TO FEDERAL GOVERNMENT
COLORADO, 1968
LEGEND
Reserved Mineral Rights
● Less than 1/4 of township reserved
Rights to all or some minerals severed from surface rights
and reserved to the federal government
Denver
Pueblo
Greeley
Ft. Collins

Fig. 108 - Areas of Colorado where the surface has passed from federal ownership but the rights to at least some minerals have been retained by the federal government.

Preceding page blank

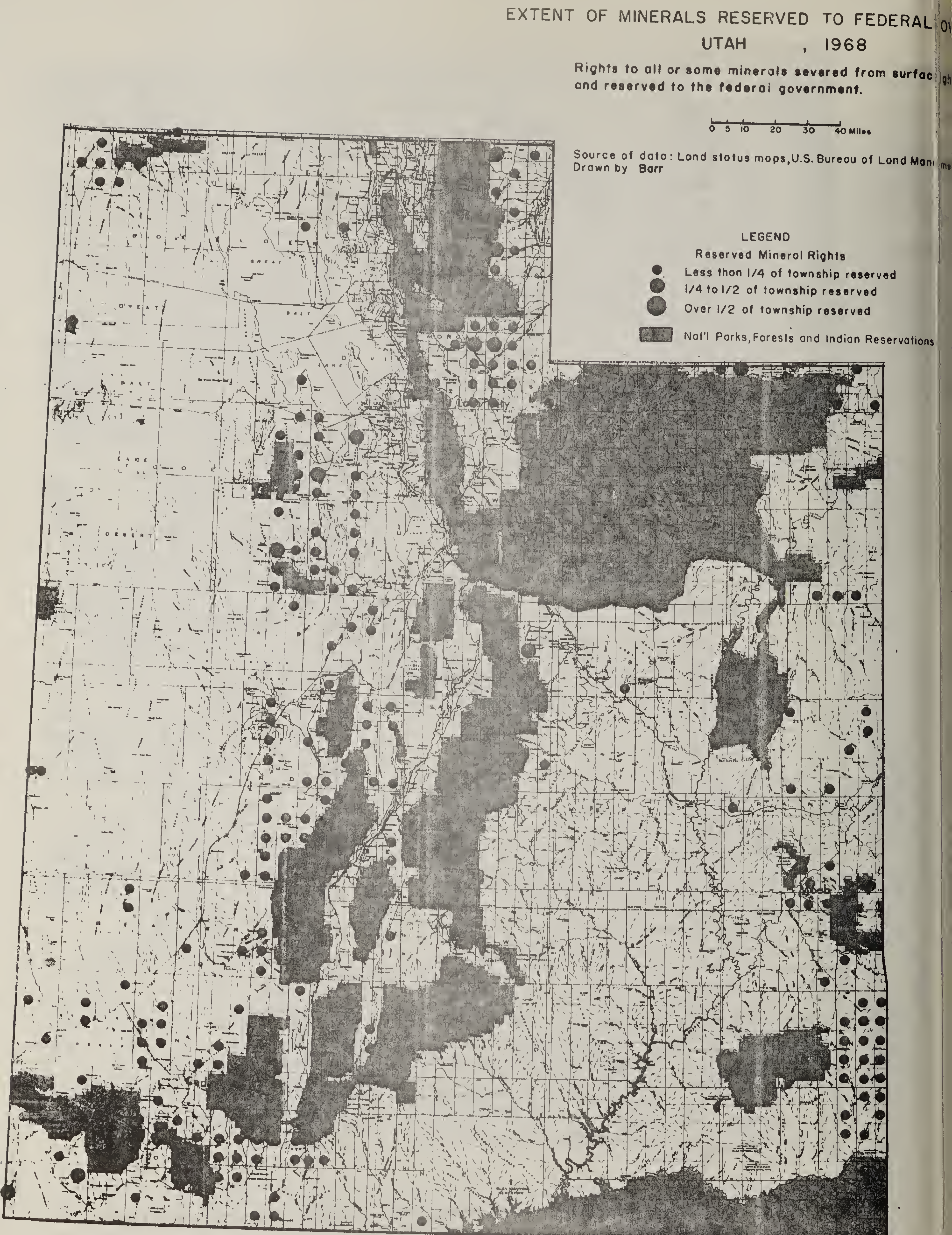

EXTENT OF MINERALS RESERVED TO FEDERAL
UTAH , 1968
Rights to all or some minerals severed from surfac
and reserved to the federal government.
0 5 10 20 30 40 Miles
Source of data: Land status maps, U.S. Bureau of Land Man
Drawn by Barr
LEGEND
Reserved Mineral Rights
Less than 1/4 of township reserved
1/4 to 1/2 of township reserved
Over 1/2 of township reserved
Nat'l Parks, Forests and Indian Reservations
Moab

Fig. 109 - Areas of Utah where the surface of the land has passed from federal ownership but the rights of the minerals thereon have been reserved to the federal government.

CHAPTER 7

THE SEARCH FOR MINERALS

Have any significant changes occurred in the search for nonfuel minerals in the United States since 1872? Since 1920? What factors have influenced these changes? Have any such changes since 1947 followed discernible trends which might be projected to 1985?

A. THE EXPLORATION PROCESS

1. The Purpose of Exploration

An *orebody*, strictly speaking, is that part of a mineral deposit which can be mined at a profit under contemporary technical, economic, and legal conditions. Economic conditions and technology are constantly changing, as are the laws and policies of governments. All of these factors dictate whether or not, at any given moment, a mineral deposit or any portion of it is an orebody. There is no arbitrary grade, size, or other set of conditions which dictate whether a deposit of a specific mineral is or is not an orebody. Hence, mineral exploration is the search for, and evaluation of, mineral deposits which have the *potential* of becoming orebodies under current conditions or under conditions expected at some foreseeable date in the future.

Prior to World War II, deposits of uranium minerals were of little interest other than academic, but they became quite valuable in the 1950's. Federal restrictions and subsequent reductions in government buying programs later caused many uranium deposits to lose their value. Some of these restrictions have since been lifted, and projected increases in demand for uranium in the 1970's have resulted in intensive new exploration for the radioactive metal. This change will probably cause many unworked deposits to regain their value and many old mines to be reopened. The "prudent man" (see Chapter 16) engaged in uranium minerals exploration, therefore, does not restrict his efforts to those deposits which are (or can be) profitable only under currently known conditions. The same is true in exploration for all minerals.

2. The Phases of Exploration

Mineral exploration generally starts with the definition of commodities, or groups of commodities, for which a search is to be conducted. Areas known or suspected to have the potential for valuable mineral deposits are selected and covered by *regional reconnaissance*. This regional reconnaissance may simply be covering the ground on foot, looking for signs of appropriate mineralization, or it may include any combination of geologic mapping, airborne geologic inspection or geophysical prospecting, ground geochemical and geophysical surveys, or regional geologic study and the interpretation of aerial photographs or the results of remote sensing surveys. A major portion of minerals exploration today is directed to the finding of geologic, geophysical, or geochemical features or other minerals likely to be associated with ore minerals, rather than for definite exposures of ore minerals themselves. Most of the obvious direct ore exposures in the United States have long since been found and mined.

Once evidence is found and judged to be favorable for valuable mineral deposition, exploration is narrowed down to the target area containing this evidence. This area is subjected to more detailed examination, using one or more of several exploration techniques, in the phase of exploration termed *target area examination*.

Based on the available information, its interpretation, and geologic theory, one or more specific targets are selected which are then normally examined by some form of excavation. This may be the drilling of diamond drill or other sample holes, trenching, shaft sinking, or tunnelling. Drilling is the most common method used today. If the initial drilling intersects ore-grade material, or material containing significant quantities of ore minerals, or strong new geological evidence sufficient to indicate the presence of an orebody nearby, exploration will continue. If not, the examination of the target area may be halted.

In oil and gas exploration, the specific target is normally large and one hole may suffice to prove or disprove the presence of valuable minerals in producible quantities. Furthermore, in the search for oil and gas, if an exploratory drillhole intersects an oil or gas deposit that is useable, then production (and income) from that deposit can be started immediately, using that same exploratory excavation (the drill hole) as the recovery conduit. Such is not the case with hard minerals. Most metallic and many non-metallic mineral deposits are considerably smaller than most oil fields and their mineral values are distributed irregularly. Many exploratory holes must be drilled before an orebody can be delimited, and such exploration requires considerable time and expense. More than 10 holes were drilled on the Mission disseminated copper orebody south of Tucson, Arizona, *before the initial discovery of valuable mineral* was made, and more than 100 holes were drilled *before an actual orebody was defined.* This is typical of the exploration process today.

If the initial drilling is favorable, the *deposit evaluation* phase is begun, and a "tracking" program is set up using widely-spaced holes to determine the location of ore-grade material and its extent. Once this is done, and if the results are still favorable, ore mineral distribution is outlined more precisely by a series of closely spaced holes located to fill in the gaps between earlier holes. If a coherent mineral deposit of sufficient size and grade can be outlined to constitute a potential orebody, feasibility studies are made to determine whether or not the deposit can or should be mined under contemporary economic conditions, and if it can, how.

These studies may indicate that, although current circumstances are unfavorable, foreseeable changes in both economics and technology may make the deposit an orebody at some future date. Under normal conditions, the deposit is then retained until favorable conditions either arrive or are created (through technology changes), whereupon the deposit is developed for production. For example, Kennecott's disseminated copper deposit near Safford, Arizona, was discovered in the mid-1950's. The deposit is low-grade, however, and is relatively deep, the top of the deposit being more than 500 feet below the surface. Research directed toward making technical and economic conditions more favorable is still in progress. Currently, the deposit is the subject of a proposed joint Atomic Energy Commission-Kennecott Copper Corporation project (Project Sloop) to test the feasibility of shattering the ground with a nuclear device exploded underground and subsequently leaching the copper from the shattered rock in place. Other examples of induced technological change are common throughout the history of mining.

3. Exploration Objectives

At present, although immediately useable deposits are always preferred, much exploration is aimed at the discovery of the complex, lower-grade, deeper, and more remote mineral deposits which may be brought into production within ten years under the economics and technology of the future. Current exploration, however, is carried on under today's conditions of competition for land and labor, with history providing the framework for investigation and the future providing the definition of an orebody.

Each of the major phases of the exploration process is likely to have its own specific objectives. It is axiomatic that there are many conditions governing minerals exploration activity at any particular time and that at some other time, some or all of them will be changed. For example, a favorable change in the international outlook for chromite prices, the depletion of a major existing chromite orebody, or the development of an appropriate geophysical exploration method would undoubtedly bring about new exploration efforts for chromite. A new metallurgical enterprise, political rejection from a chromite-producing nation, or a new geologic view of the ultrabasic intrusive igneous rocks commonly associated with chromite could have the same effect. Very few of these conditions are under the direct

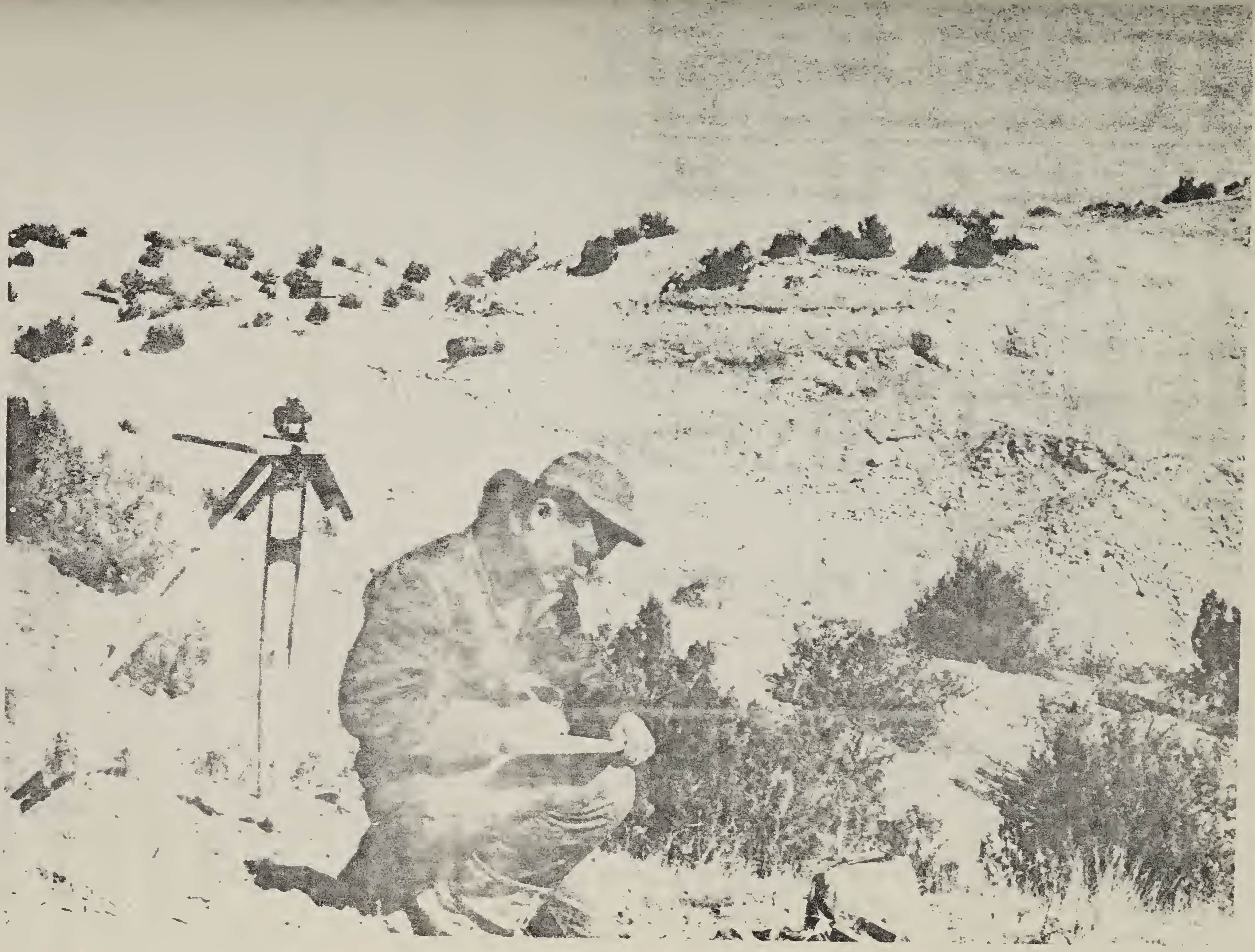


Fig. 1 · A geologist mapping surface and geologic features in the initial reconnaissance phase of minerals exploration. Such field activity is supported by extensive office and laboratory work in the search for potential mineral areas. (Photo courtesy of Thomas Nye.)

Table 1

THE MINERAL EXPLORATION PROCESS

I. *Preliminary Preparation*

  A. Selection of program criteria

    1. Selection of commodity or commodities to be sought
    2. Selection of general guidelines for deposit location and characteristics

  B. Familiarization

    1. Review of available literature
    2. Review of known areas of mineral occurrence
    3. Review of property submittals and reports
    4. Analysis of the geology and projection of trends of structure and rock formations, with the aid of maps and aerial photographs
    5. Selection of regions for reconnaissance

II. *Regional Reconnaissance*

  A. Geologic reconnaissance

    1. Airborne reconnaissance: search for color or topographic anomalies
    2. Ground reconnaissance: search for color, petrological or mineralogical anomalies
    3. Examination of project submittals and prospects
    4. Reconnaissance geologic mapping

  B. Geophysical reconnaissance

    1. Airborne
    2. Ground

  C. Geochemical reconnaissance

    1. Of streams draining large areas
    2. Of color and geophysical anomalies and/or significant areas detected by geological reconnaissance

  D. Determination of land status

  E. Selection of target areas

III. *Land Acquisition*

  A. By staking

  B. By lease with option, from private owner

  C. By prospector's permit, state or federal

  D. By state or federal lease

Table 1 (continued)

IV. *Examination of the Target Area*

- A. Detailed geologic mapping
- B. Detailed geochemical surveys on the ground
- C. Detailed geophysical surveys
- D. Mineral and rock analysis by microscopic and X-ray techniques
- E. Evaluation of data
- F. Selection of specific deposit for evaluation
- G. Fund allocation, road construction, and drill site preparation

V. *Physical Testing of the Target Deposit*

- A. Initial drilling (one to five holes)
    1. Log core and/or cuttings
    2. Split samples and have them assayed
    3. Record and plot data
    4. Draw projections of data
    5. Analyze data and evaluate
    6. Decide to continue or abandon project
- B. Follow-up drilling
    1. Log core and/or cuttings
    2. Split samples and have them assayed
    3. Record and plot data
    4. Draw projections of data
    5. Analyze data and evaluate
    6. Track ore mineralization and/or ore mineral indications
    7. Decide to continue, abandon, or postpone project
    8. Adjust area controlled
- C. Drilling to define the mineral deposit
    1. Log core and/or cuttings
    2. Split samples and have them assayed
    3. Record and plot data
    4. Draw projections of data
    5. Analyze data and evaluate
    6. Track ore mineralization and/or ore mineral indications
    7. Correct outline of mineral deposit from new drill data
    8. Estimate tonnage and grade of deposit

VI. *Evaluation of the Results.*

- A. Make bulk analyses, metallurgical, economic, and engineering feasibility studies
- B. Decide to mine, hold in reserve for more favorable conditions, or drop the property

control of an exploring individual or organization, but all are subject to estimate and to practical projection. Many conditions are also subject to personal bias in their interpretation. This personal factor is called "irresponsibility" following a failure or "keen foresight" following a success.

The compilation of geologic and economic data for a region under consideration is a first step in mineral exploration, but an equally important preliminary job in any exploration effort is a study of related case histories with all available information on expenditures and decisions. Good case histories can usually be found quite readily in the mining journals. Recent examples deal with the Questa molybdenum deposit (Schilling, 1965), the Carlin gold deposit (McQuiston and Hernlund, 1965), the Irish Silvermines lead-zinc deposit (Weber, 1964), and several Australian deposits (Lawrence, 1965). History, in respect to successful exploration ventures, emphasizes the timely use of new developments under existing conditions. In studying successful past ventures, the capital required for developing similar orebodies under today's economic conditions must be kept in mind. For example, the Wallaroo and Moonta orebodies in South Australia which actually returned 15 percent to investors during a 50-year period would present an unfavorable aspect under today's economics because the necessary investment would have a comparatively long payout period of 30 years.

If any one central theme can be said to occur in case histories (other than luck, the prospector's goading spirit), it is the repeated importance of continuing *evaluation and re-evaluation* in the light of the estimated risk and the expected profit after each exploration step and with each new expenditure. Each run of drill core and each new look at the assembled geologic data is likely to change the economic and technical relationships. The risk vs. profit relationship changes with new mining concepts, with regional economic development, and with new company or governmental attitudes. Each exploration team has a different set of conditions to evaluate. Each team, in essence, has its own set of exploration rules. This is why a majority of new orebodies have been found in districts which have been examined, explored, and even mined repeatedly, sometimes by the same company. It is no wonder that many exploration men keep recalling the prospect which they rejected five years ago and would now like to re-examine. The mineralization will not have grown in five years, and the law of gambler's ruin will not have been repealed in order to allow for six more drill holes, but the economic environment, the level of geologic knowledge, and the technology of exploration and production will most certainly have changed.

An exploration effort may consist of a series of old-fashioned but still completely applicable and necessary prospect examinations. It may involve a modern regional selection program, or it may be a district task-force job undertaken to replace a depleting orebody. In any event, a minerals exploration effort is a sequence of investigations and decisions in which the experience of past failures is just as important as that of past successes. A major requirement, therefore, is a continuity of experience. It is thus not economical for a minerals firm to make drastic reductions in exploration personnel in times of recession and then expect a totally new organization to discover orebodies quickly in times of brighter outlook.

The exploration team of engineers and geologists must have, in addition to education and imagination, a thorough understanding of the current objectives and economic capabilities of the organization. A small exploration organization with good management communications can thus compete very well with the larger and more unwieldy "opposition." Similarly, the small miner-prospector with a personal interest in a particular area often can do a much better job of deposit-finding than larger, more sophisticated organizations. In fact, the small miner-prospector may often provide the continuity of information needed for successful performance by the larger exploration organizations.

As many exploration decisions as possible should be made in the field by qualified men familiar with the job and with the objectives of the firm. If the head office changes the exploration plan or preempts funds and personnel for a more attractive venture, the decision should be fully explained to the field men. Such is part of the pattern of company objectives under which they will continue to operate in the future. By understanding the economics of company objectives, field men can differentiate between interesting but fruitless tangents and potentially important windfalls. As a case in point, the iron ore deposits of the Labrador Trough were not the objective of the base metal exploration efforts in the area in the early 1940's. The side issue of new iron ore discoveries, however, was recognized as an important opportunity and soon provided the opening chapter to one of the great mining stories of the century.

An exploration effort, like most aspects of the mineral industries, has a great number of "if" statements. "If" exploration is being conducted in central Alaska, the minimum objective of the effort may be on the order of several million tons of accessible high-grade mineralization or it may be a hundred million tons of near-surface, low-grade mineralization. With such threshold values, a major portion of the exploration budget must go into *reconnaissance* work with airborne and broad-scale methods directed to bringing out the largest and most obvious targets in a limited time and at a low cost per square mile. Programs making good use of reconnaissance work are reported in case histories of the Kidd Creek orebody (Mitchell, 1964), the Bathurst-Newcastle district of New Brunswick (MacKenzie, 1958), and Central Labrador (Hogg, 1966). With the necessary low unit area costs for exploration and land acquisition, a large profit (relative to expenditures) will accrue to the earliest company involved in the finding of a new zone of mineralization. The discovery may result, however, in a "holding property" from which profit is delayed until there are favorable changes in the economics of the area or of the commodity. At any rate, companies arriving on the scene at a later date with pay a premium in order to obtain a piece of the good fortune under conditions of reduced risk.

If exploration is being conducted in a well-established mining district, in Arizona or Nevada, for example, the minimum exploration objective can be more flexible. A deeply-buried or low-grade orebody can be perfectly acceptable near an already established large-scale mining operation. The deep Kalamazoo orebody near San Manuel, Arizona, and the relatively deep phosphate reserves at Crawford Mountain, Utah, near the Leefe open pit mine and processing plant, are illustrative examples. In fact, even a rather small orebody is important when mining, processing, and transportation facilities are close at hand. This is especially true if the known orebodies are soon to be exhausted. The key which opens a new producing mine is thus held by the established local operating companies. Their attitudes and the availability of their facilities are therefore of major importance. An existing and fully-amortized beneficiation plant is an asset, *but only to the owner.*

Because its objectives and results must be more precisely defined, exploration budgeting in an established district must make provision for detailed geologic work, extensive drilling, and high-resolution geophysics. Underground exploration in new mine workings may be required, and the cost of such methods relative to the information obtained generally has not decreased in the same manner as the cost of reconnaissance. Land acquisition and royalty-purchase payments are normally large and complex items. Large total profits are obtainable, but under such conditions there is little opportunity to be the first on the scene with a high ratio of profit to exploration cost.

The range in objectives for individual projects can be further illustrated by considering the economics of finding an orebody with a high unit value versus the cost of finding a bulk, low-grade orebody. In the high unit value instance (typified by many uranium deposits on the Colorado Plateau), relatively high exploration, mining, processing, and shipping costs per ton of ore can be accepted. There is an opportunity for an early return on investment, provided the pre-production investment is small to moderate. Risk capital for such ventures generally requires an early return. Ore reserves can be indicated in a very general way, for the main geologic problem is in finding ore mineralization in the first place.

The definition of a commercial orebody in such high unit value deposits in order to separate *exploration* work from *development* work requires only enough ore to support a small-scale operation. Development, mining, and the delimitation of the orebody then go ahead in close association until enough ore has been outlined to warrant the obtaining of capital for an expansion project, a new tunnel level, or a large processing plant. Exploration costs for high unit value targets are mostly incurred by the search for ore-grade mineralization. Such search costs have a risky and expensive "needle in a hay stack" aspect. The *pre-production* cost of outlining, investigating, and developing the orebody is kept relatively low, but the calculated cost per ton for mining and processing may be relatively high. This is the typical pattern of exploration and mining for shallow-seated uranium and mercury deposits and for many orebodies such as the early gold and silver deposits of the West.

Bulk low-grade orebodies of copper, molybdenum, complex base metal ores, many industrial minerals, and even disseminated gold are receiving current emphasis and now account for a substantial percentage of the world's mineral production. For such deposits, even though the *total* cost of finding large zones of mineralization may be considerable, the reconnaissance cost *per ton of anticipated ore* must be kept quite low. The major exploration and development costs relative to each ton of ore generally occur after mineralization has been found. They involve the outlining of the entire orebody and the close estimation of grade, mineralogy, geomechanical conditions, and groundwater conditions. A large pre-production investment is usually anticipated, and there is a need for a low cost per ton in mining, processing, and shipping.

Pre-production capital is irrevocably committed once the green light is given, however, and such operations cannot be financed on the basis of hastily executed exploration and development programs. This is the major point of difference in the economics of exploration between targets involving bulk low-grade orebodies and those involving high unit value orebodies. Repeated economic analyses and alternative programs are made from the very early exploration stages onward, and the effort calls for close cooperation between geologists, metallurgists, and mining engineers. As much precision is required as can be afforded by the profit versus risk picture. With sketchy geologic data or with a limited exploration time, the economic analysis must be made to provide large safety margins, so much so in fact, that an entire project may be prematurely abandoned in favor of a less risky opportunity. Field crews, however, often lose sight of the fact that their particular indefinite "baby" must compete with other well-investigated demands for available capital. The objective of an exploration program thus is normally established as early as possible and reevaluated as often as practicable. This avoids unrealistic expenditures early in the effort and permits the funding of detailed work when it is most critical.

In many respects the various phases of exploration and the objectives of those phases have not varied significantly since the period prior to 1872. The relative importance of the different phases has changed, however, and this, combined with changes in the types of deposits sought, has wrought significant changes in the minerals exploration process.

B. MINERALS EXPLORATION BEFORE 1872

1. The Exploration Process

Although terminology differed, and the more elaborate techniques and equipment known to modern geologists were not available to the early prospectors, the phases of the exploration process used in the period prior to 1872 were essentially the same as they are today. True, the *target area examination* and *deposit evaluation* phases were often condensed and overlapping, but they did exist, and in that order, despite the fact that they also frequently overlapped or were coincidental with the development and production stages of mineral resource utilization. To the early placer gold seeker, his initial panning, if it yielded some gold, was not only his target examination but also his deposit evaluation and the beginning of his production. In many vein and other early deposits, the exploration was never really finished until the orebody had been mined out. In certain respects this is still true today. Then, as now, minerals exploration involved essentially a search for anomalies and then the evaluation of those anomalies that were found.

Before 1872, mineral exploration in the Western United States was mainly concerned with the search for silver and gold in California and the Mountain West. Such exploration was really more prospecting or reconnaissance, for exploration as presently defined includes the outlining of a known potential deposit to determine its tonnage and value, although in current mining parlance the two terms are often used interchangeably.

Before 1849 the only kind of prospecting in the West was carried on in the Spanish-Mexican tradition and was limited to the almost chance discovery of outcrops of silver ore which could be smelted in crude furnaces with charcoal and then (after the discovery of the patio process by Bartolome de Medina about the middle of the Sixteenth Century) reduced and amalgamated with mercury imported from Spain. In fact, it was a "silver" mine that Andres Castillero, a Mexican cavalry captain (who had been sent by his government in 1845 to confer with General Sutter about the purchase of his fort), discovered near the Mission of Santa Clara, California, only later to find that it contained mercury rather than silver.[1]

This early Mexican tradition was of little account in the early 1850's when prospecting in the West was hardly more than a savage onslaught on the placer deposits in the streams and rivers of California by men with no experience who searched aimlessly, hoping that chance would bring them to a find like that of Marshall in the tailrace of Sutter's mill. Only later did they come to realize that a straight run of stream was to be avoided and a bend with a sand bar was a place to be dug with alacrity. Yet it is in these earlier conditions that early mining law had its origins.

Common law at the time implied that the finder of gold had a right to it as well as to access to water independent of the normal landowner's equity, and that where there was no established law, local citizens could legislate for their needs. As a result, early miners and prospectors in California organized themselves into public meetings and on the spot argued and ratified their understanding of placer law.

It became fairly general in California, and elsewhere in the West, that a placer mining claim was between 50 and 100 feet long, extending along the channel of a water course and sufficiently back to the banks to allow a claim to be worked. The claim had to be located and marked in some way or other, recorded, and a pit put down. No man could possess more than one claim at a time, though there were no objections to an association of partners to work several claims. In all cases a certain amount of work had to be performed on the claims for a specified time; otherwise, they were regarded as abandoned. No one had the right to take more water than he needed nor could he dump spoil that was likely to impede the work of others. At its best the law was reasonable and sensible, and disputes could be settled either by the recorder of claims or, in more difficult situations, by an elected tribunal of the miners themselves.

By 1851 almost every fluvial claim in California had been exhausted and the search for

Fig. 2 - Minerals exploration methods in the 1800's were comparatively simple and restricted the work done by any one person to a relatively small area. The miner's pan was (and still is) one of the most useful of exploration tools. (Photo courtesy Arizona Pioneers Historical Society.)

new deposits took the form of an attack on the great gravel banks of the Sierras by the process of hydraulic mining. By the time these also were exhausted, ten years of accumulated experience had produced a corps of prospectors who were to find new deposits all over the country and the world. The change, imperceptible at first, could be said to date from the 1850's when the California Mother Lode was found and the Comstock Lode was uncovered in Nevada. The change accelerated in the 1870's.

The old-time prospector may have worked by rule-of-thumb methods, but he possessed a remarkable eye for landscape as he searched systematically for orebodies. He knew almost instinctively where valuable minerals had most likely been trapped and so came to prefer a landscape which revealed some deep faulting or cracking in the earth's crust (as in the Basin and Range country), some powerful upwelling of the magma (as in the Sierra Nevada and the rounded domes of the Rockies), and other obvious igneous intrusions. His guiding principle was that the older and the deeper the rock, the higher would be the chance that it would be mineralized. So it was thât he avoided the cinders and lava flows of basic vulcanism and preferred the unpretentious batholiths and laccoliths and the sedimentary formations that had been shaped by crustal movement or by igneous action from below and into which magma had been intruded.

What his experienced eye was looking for, as he worked in isolation, was the "float" in outwash gravels, the minute particles of gold that had been eroded away from a vein by the action of running water, for he knew that if he could trace the "float" back up a stream he might arrive at its source. He had his own methods of testing the difference between the real gold and "fool's gold" by cutting them with a knife and "tasting" them in his mouth, and he knew the importance of examining carefully the physical state of the gold particles or the rock in which they were contained. If they were round and smooth, it meant that they were far from the source of origin; but if they were angular, it meant he was not too far from their main supply.

In the early days of placer mining, the prospector might do no more than begin operations at a favorable site on a promising stream, dig a prospect hole down to bedrock, and inspect his soil samples. After that would follow dry sampling or panning, depending on whether water were readily available or not. This would be followed by crude testing for gold.

As the richest placer deposits became discovered and worked, however, the prospector's search for orebodies became a much more sophisticated affair. One widely used method involved first digging test-holes over a wide area of ground, not at random, but according to a preconceived plan, taking out soil samples and washing them by panning. These were worked gradually up a slope following one contour and then another, with the prospector even looking for the dirt thrown up by burrowing animals in case they might have exposed some rock, until no more *float* was to be found and until the trial holes assumed the pattern of an extended triangle with its apex pointing towards the probable source of the gold *float*.

If no outcrop were visible, it would be assumed that the soil covered a hidden outcrop. It was also known, however, that an outcrop was not usually ore-bearing throughout its entire length. More digging would therefore follow, with pits or trenches until there were signs of gold trapped in pieces of gangue.

The prospector then made a rough but adequate on-the-spot calculation of the rock's gold content. A small sample was taken (usually about one pound in weight) and ground in an iron mortar. To it were added mercury, salt, and soda. The resulting mixture was poured off until finally a tiny pellet was left behind, the amalgam of mercury and gold. This was then tightly wrapped in a piece of paper, roasted on a shovel to drive off the mercury, and the bead or button of gold revealed.

The prospector finally made his own estimate of how much the ground was likely to assay in gold to the ton of ore. All that now remained to be done was to stake out his claim to a vein or lode (and he knew the regulations to the last detail) and visit the recorder and the professional assayer. Such was the way that prospecting was carried out until the arrival in the field during the late 1860's of the professionals from the various schools of mines, expecially those in London, Cornwall, and Freiberg, to begin with, and then later from the American schools.

2. Reconnaissance Methods

In discussing mineral exploration methods and techniques in the period prior to 1872, it is useful to treat separately regional reconnaissance, the examination of known mineralized districts, and the evaluation of specific mineral deposits. The methods and techniques of the three activities differed greatly in the 1800's, and in many cases still do.

An exploration *target* is a mineral deposit, real or hypothetical, which is believed to have profit potential. A *target area* contains a combination of geologic (including geochemical and geophysical) clues which point to the possible existence of a profitably mineable mineral deposit. A target area is limited in size, in which one or more specific exploration targets (i.e., potential mineral deposits) exist.

In the period before 1872, known target areas in the Western United States were found by both regional reconnaissance and accident. Specific targets also were commonly the result of regional reconnaissance or accidental discovery, but some also were defined on the basis of the exploration of known mineralized districts.

Reconnaissance methods and techniques in use in the 1800's can be conveniently classified in two categories, geologic and geochemical. Geologic methods and techniques can further be classified as: topographic; mineralogic (including ore minerals, gangue minerals, and gossan minerals); alteration haloes; lithologic and stratigraphic; and structural, including fracture patterns, contacts, and folds. Geochemical methods and techniques included both the sampling of stream sediments, and residual and transported overburden, and what we now call geobotanical methods. A third category, which constitutes a third main type of exploration methods today, is the geophysical method. Geophysical methods were not in use in the western states in the period before 1872, however. Many of the geophysical methods in use today were at best in their infant stages of development during the period, and in some cases even the mathematics which would permit rational analysis of data had not yet been devised. Shortly after 1872, such methods were introduced. Magnetic measurements were conducted in the Michigan iron district in 1873 and in 1875, and in 1882 an electrical survey was made at the Comstock Lode.[2]

The following excerpt from a paper read in Australia in 1939 describes mineral exploration methods of the early prospector. It is just as descriptive of the exploration methods of the prospector in the Western United States in the 1800's as it was of the Australian prospector in 1939.

> "Everyone knows the term 'kindly country' as used by miners and prospectors. Sometimes one part of an area is said to be 'kindly' because it differs lithologically from another part, which is 'unkindly.' Thus, in Western Australia 'greenstone' country (i.e., country comprised of ancient basic igneous rocks) is 'kindly' for gold, whereas granite country is 'unkindly.' But the experienced prospector goes further than this–the presence of certain igneous intrusions in a greenstone area tells him that it is kindlier country than a greenstone area devoid of such intrusions. Further, other things being equal, he knows that a greenstone area that is soft and schistose is kindlier than one that is hard and blocky, and, going into still more detail, he will prefer one area of schistose greenstone to another perhaps because it has more 'kaolin' or shows little seams of 'ironstone,' or, in the unoxidized zone, because of some perhaps scarcely definable difference in the grains of pyrite. In short, the experienced prospector regards as reliable indications, first the lithology, second the structure, third the mineralogy, of the country near the lode. The lithological factor is the dominant one; for example, an area of sheared and sericitized granite is not kindly–the favorable structural and mineralogical features are altogether neutralized by the dominating fact that lithologically the country is unkindly. Further than this, the man of wide experience knows that what are unfavorable indications in one district are not necessarily unfavorable in another.
>
> "Mining geologists have, to a certain extent, systematized accumulated experience into such statements as 'Important gold bodies occur in certain types of greenstone and are situated in definite positions structurally'–for example, in one district, on the limbs of minor folds that cross the main structures. But everyone knows that, given these favorable conditions of lithology and structure, ore-bodies will not necessarily occur, nor can one be sure that, if ore-bodies do occur, they will be much good."[3]

In using topographic guides to ore, peculiarities of topography, such as a small knob jutting through an otherwise flat alluvial plain, or a bold dike standing several feet up against the skyline on a relatively smooth ridge, caught the eye of the early prospector. Quartz veins, dikes high in quartz content, and masses of rock into which silica has been introduced often form prominent outcrops. Quartz resists weathering, and the erosion of quartz-rich (silicified) rock will often take place at a slower rate than the erosion of surrounding quartz-poor rock. In many early mining districts of the West, precious and base metals occurred in well-developed quartz veins. Realizing the common occurrence of these situations, early prospectors looked for bold outcrops. When discovered, they were examined for indications of metal content. Usually pieces of quartz, if present, were broken from the outcrop, crushed, and panned. Samples might also be sent to assayers in established camps, or in towns such as San Francisco or Denver.

Valuable deposits were not always marked by prominent outcrops, and with experience prospectors became aware of this. Some ore minerals weather faster than the rock in which they are contained, and small depressions will form over deposits of those minerals. This is particularly true of some types of lead and silver ores. Thus a prospector might be attracted to the more obscure parts of a vein whose outcrop was prominent at some places, but indistinct at others.

In using mineralogic guides to ore, the presence or absence of certain minerals in rock masses was recognized as a valid criterion for judging the relative merit of outcrops. In order to make good use of this criterion two capabilities were necessary: (1) the ability to identify minerals, and (2) the ability to determine the significance of the mineral in a specific environment. While early prospectors frequently had reasonably good capabilities in the area of mineral identification, they were just as frequently misled by a lack of ability to determine the significance of a particular mineral in a given environment.

The ability to identify minerals by means of simple physical and chemical tests was as essential to prospecting in the 1800's as it is today. Some minerals have very characteristic colors and/or crystal forms which were often sufficient in themselves for identification by an experienced prospector. Two minerals similar in appearance may often be distinguished by their relative hardness. One may be grooved by a penny while the other will only be scratched by a sharp knife or a piece of broken glass. Gold flattens when hit with a hammer, while fool's gold (iron pyrite) powders. The usefulness of easily determinable or readily observable physical properties in mineral identification is indicated by some common mineral names such as: heavy spar, blue vitriol, horn silver, peacock copper. Simple chemical tests such as solubility in weak acid solutions were also known to and employed by some prospectors well before 1872.

The most encouraging minerals were those of valuable metals, but gangue minerals were also useful guides to the early prospector. The gangue minerals of a deposit accompany the ore minerals, but are either worthless or cannot be recovered in saleable form. Gangue minerals were of definite interest to prospectors as indicators of possible, nearby, valuable mineralization. Two of the most common gangue minerals are quartz and iron pyrite. Pyrite is usually very readily identifiable due to its common cubic shape and brassy yellow color. It is of extremely widespread occurrence in Western metal mining districts.

The outcrops of a large number of deposits of gold, silver, copper, lead, and zinc, as well as other metals, are marked by varying quantities of conspicuously rust-colored iron oxide. The iron oxide results from the weathering of iron pyrite, a compound of iron and sulfur, and of other minerals, notably copper minerals, which contain sulfur and often iron. This prominent iron oxide was referred to in the old days as a *gossan* or *iron hat*. It is one of the oldest known clues to the existence of ore deposits, and even in the 1800's only a greenhorn would have passed up an apparent gossan without giving it a look.

Alteration haloes are formed by the processes by which valuable minerals become concentrated in mineral deposits, often producing side-effects (known as alteration) in the rock surrounding the mineral deposit. The changes in the surrounding rock may be physical and/or chemical. In many cases such alteration was readily detectable to the prospector.

In these alteration zones, limestone may be turned to marble; shales may be turned into flinty hornstones; dark rocks may be bleached; and scattered grains of pyrite may form. Upon weathering and leaching of the pyrite, a red iron oxide capping may form over an area of tens of acres. This latter phenomenon is the same as that resulting in the formation of gossans over veins or lodes, except that the weathering pyrite is scattered throughout a larger volume of rock. In the period before 1872, as today, prospectors looked for such alteration features as guides to ore.

The rock types found in an area constitute the lithology of the area. It has long been recognized by prospectors that in a given district, one rock type will be a favorable host for mineral deposits while other rock types will not. The excerpt from the article by Clarke and Ellis, previously quoted, illustrates well the use of lithologic guides by prospectors for gold in Australia. Greenstones are better than granites, and greenstones which have been cut by certain igneous intrusive rocks are better than those which have not been so invaded.

A very similar situation prevailed in the California Mother Lode country. Prospectors looking for gold veins sought "slate country." And when they went out of the mother lode into districts in other states, they carried with them the idea that gold would be found in *slate country*, but not just any kind of slate. The slate must be like that of California.

While it is frequently safe to apply a particular lithologic guide to a district, it is often hazardous to transfer it from one district to another. Thus, the fact that rich silver ore occurred in andesite at the Comstock Lode in Nevada did not mean that it was likely to be found in andesite in every silver district. And while *slate* may have been the favored host rock in the Mother Lode country, gold veins might be (and have been) found in andesite in another district. Within limits (and these may be quite broad limits), lithologic guides to ore are very useful. But early (and more recent as well) prospectors expended very large amounts of effort and money fruitlessly on account of ill-advised transfers of lithologic guides from one region to another.

Closely related to the use of rock types as guides to ore is the use of specific rock formations. Layered rocks are commonly referred to as strata. Thus, if one limestone bed contains copper deposits, while the underlying and overlying beds do not, the presence or absence of the favorable bed is referred to as a stratigraphic guide. Stratigraphic guides, then, are actually a sub-type of lithologic guides, and were likewise used and misused by early prospectors.

Fractures, folds, and some other features of rock masses constitute what is known as the structure of a rock mass. Veins very often fill fractures, and in a given district, fractures of one orientation often will be found to be more favorable for ore deposition than those of other orientations. Moreover, fractures along which there has been movement of the rock walls may be more favorable than fractures along which no movement has taken place. There may be zones of broken rock in folds in limestone or other layered rocks. These broken zones provide paths through which fluids containing valuable metals can pass, perhaps depositing some of the metal.

In some districts, fluids carrying metals may have risen until they encountered a dam formed by the intersection of their pathway with a deflecting impermeable bed of rock, often shale. At the intersection they deposited their load of metals. Contacts between rock types of contrasting physical and/or chemical properties thus have often been favorable sites for finding ore deposits.

All of these structural controls of ore deposits were well known to prospectors of the 1800's. The quartz-filled fracture or fracture zone probably received more attention from prospectors than most of the other guides put together. While the search for quartz veins led to many discoveries, preoccupation with quartz veins caused many promising areas to be overlooked by some early prospectors.

Geochemical methods of exploration are techniques for detecting very small amounts of particular chemical elements which may lead to mineral deposits. The techniques used usually depend heavily on chemistry for identification of the elements and the determination of their relative abundance. One widely used method involves the sampling of stream sediments and of residual and transported overburden. Residual overburden is soil which lies unmoved on the rock from which it formed. Transported overburden is soil and broken rock which has moved, typically, down hillsides.

Following a trail of gold back to its source by panning stream sediments up drainage systems is one of the oldest methods of the prospector. When the gold disappeared from the stream sediment, the early prospector moved up adjacent slopes panning overburden until, hopefully, he found the lode from which the gold derived. Other minerals are also discoverable by panning. Among them are native (elemental) mercury, mercury in sulfides, tin (as cassiterite), lead (as galena), and other heavy metals. Following mercury to its source by panning led to the discovery of some of the earliest California mercury deposits. In a few districts in which gold was associated with galena, galena was probably sought in the gold pan as well as gold itself.

For centuries, miners and prospectors have speculated about the association between certain plants and mineral deposits. The *zinc violet (Viola calaminaria)* is a well known example of such an association. A knowledge of these associations was brought from Europe to the United States by miners. It is almost certain that some prospectors in the West were aware of them, but it is not known to what degree a few prospectors may actually have attempted to use them as guides to ore. In any event, in a paper read before the American Institute of Mining Engineers in 1886, it was reported that the zinc violet had been recognized at the Horn Silver Mine in Utah, the ore of which contained considerable zinc sulfide.[4]

3. Target Examination and Evaluation

Many of the skills and guides helpful in early regional reconnaissance were also applicable to target area examination in mineralized districts and the evaluation of specific mineral deposits. However, in these latter stages of exploration, a proportionately greater amount of time, effort, and money was spent on sampling than in the reconnaissance stage.

In the 1800's outcrop sampling was usually the first step in attempting to pinpoint targets for detailed evaluation. If the samples yielded promising assays, or if insufficient outcrop were present, shallow pits and trenches would be dug. This work was all done by hand labor. In some western districts, hundreds of pits and trenches were dug on covered parts of veins, dikes, and other interesting geologic structures.

If a specific target could be identified (and often even when it could not), the next step was underground exploration. Shafts and adits with drifts and cross-cuts were driven as far into the earth as money or ground conditions would permit, or until the prospectors decided that discovery was not likely. The underground workings of this period were for the most part relatively shallow, rarely penetrating as much as 300 feet underground. The mining technology developed at the Comstock mines during the years from 1860 to 1880 changed this situation radically. By 1880 shafts had penetrated to depths of more than 2,000 feet below Virginia City. The Sutro Tunnel, the purpose of which was to permit exploration and development of the Comstock Lode at deep levels, was started in 1869 and reached the lode in 1879. By that time the lode was already being worked 1,000 feet below the level of the tunnel, however, and most of the ore was gone. The tunnel was over 20,000 feet long, and four and a half million dollars were consumed by the project.[5]

At the beginning of the 1860's, mechanical drills were not available for sampling or for driving underground workings. All drilling was done by hand-held hammers and steels. This situation began to change by 1870. Some have considered the importation of the first diamond drill into the United States from France in 1869 as the beginning of modern exploration techniques.[6] Diamond drills were used to explore deep levels in the Comstock only after 1880, however, and it was not until 1875 that a steam drill had been adopted by Colorado miners.[7]

4. Exploration Entities

Mining engineers and trained geologists were almost never used in early mineral reconnaissance. The only significant exception to this in the West was the case of the Sonora Exploring and Mining Company, which employed engineers to explore for mines and to develop and operate them in Southern Arizona in the late 1850's. Considerable use was made of engineers, however, in prospect evaluations, in district examinations, and in directing underground exploration. In the early days of the Comstock Lode, mining engineers engaged in such activity commonly worked 12-hour shifts for $100 per month.[8]

In 1880, the Division of Mining Geology of the newly established United States Geological Survey was allocated about half of the entire appropriation granted to the U.S.G.S. by Congress.[9] The first assignments of the Mining Division geologists were the Comstock Lode and Eureka District in Nevada, and the Leadville, Colorado, District. At the same time, Dr. James Douglas made a three-day examination of the Eureka and Wade Hampton claims, which turned out to be two of the best claims in the Jerome District in Yavapai County, Arizona, for a fee of $500. It is not known if the $500 was also to cover Dr. Douglas' travelling expenses from Maricopa Wells, Arizona, to the claims or if that was only his professional fee.[10]

The United States Geological Survey and professional engineers such as Dr. Douglas did not really come into prominence in the exploration for minerals on the public lands of the United States until after 1872. For a discussion of exploration entities and organizations in the period before 1872, it is convenient to classify exploration into that for new districts and that of known districts. In the years of the 1850's and early 1860's, the principal types of deposits sought by prospectors searching for new districts were placer and lode gold deposits and silver deposits, all rich enough to pay their way from the day of discovery. Exploration methods were simple, including panning up streams to find the sources of gold nuggets or crushing and panning of iron-stained rock from outcrops of quartz veins. The only costs involved were subsistence level expenditures for supplies for the normally lone prospector.

This raw exploration was carried out by lone prospectors working on their own or in partnerships. Probably most of the time the prospectors financed their own forays, but it was not uncommon for them to seek outside financing. A common form of financial

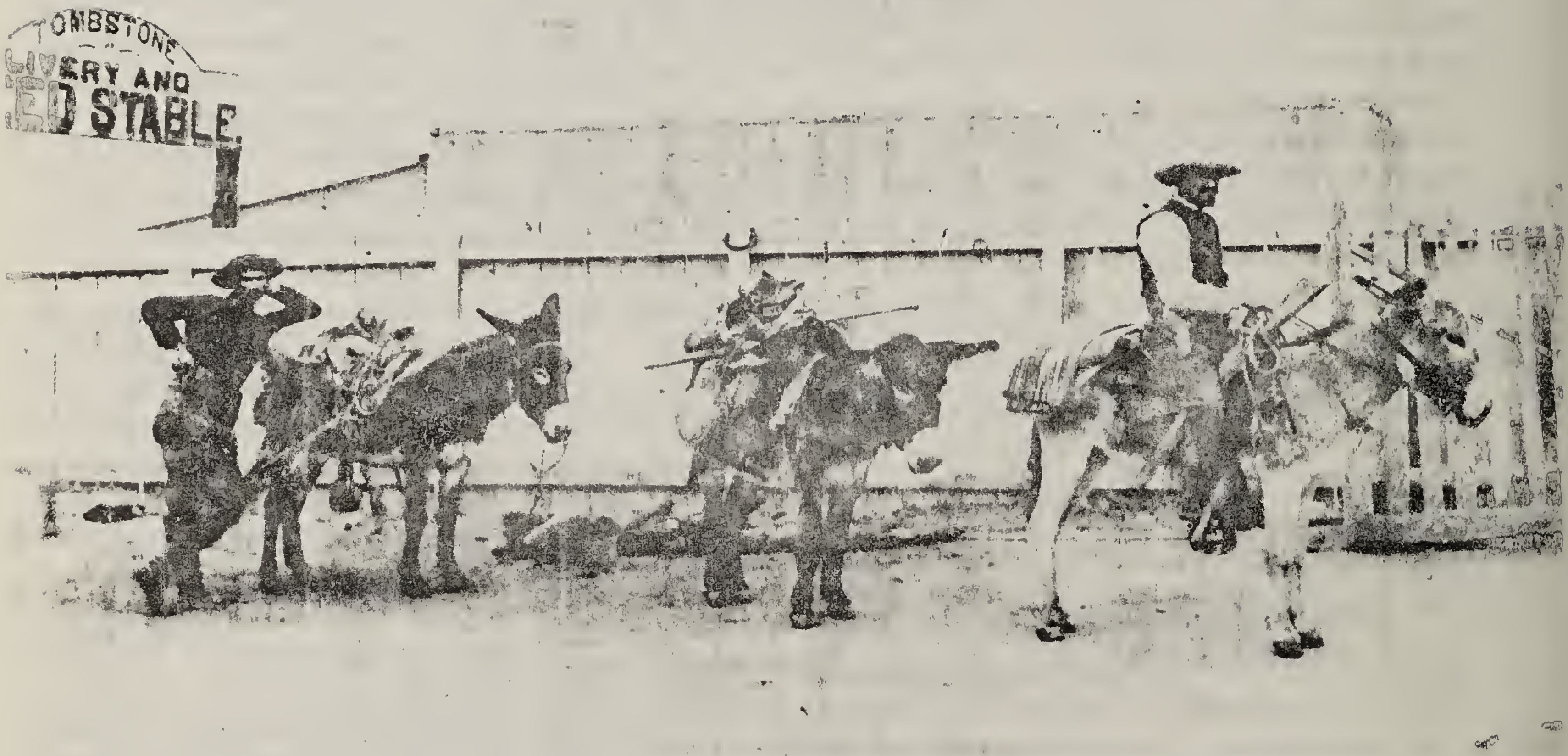


Fig. 3 - Early exploration organizations and equipment were relatively simple. Minerals reconnaissance and a major portion of detailed target area examination were performed by prospectors working alone or in partnerships. Their major targets were visual geological and mineralogical anomalies. (Photo courtesy Arizona Pioneers Historical Society.)

arrangement was the *grubstake agreement* under which the entrepreneur providing supplies would receive an interest in any discoveries made, but did not take part in the physical search efforts.

Generally, the prospectors searching for the deposits *intended* to mine them. When a new district was discovered, the initial exploration and development of the deposit was done by the discoverers. Workings in lode mines hardly ever penetrated very deeply underground, the prospectors being chiefly interested in the near-surface parts of veins which had been enriched by surface geologic processes.

It was practically unknown during the period prior to 1872 for companies to be organized actually for the purpose of carrying out exploration for new mining districts. One noteworthy exception was the Sonora Exploring and Mining Company, which was active in the exploration for the development of mines in Southern Arizona in 1856 and following years. The venture was promoted in the East by Charles Poston, who raised $100,000 for it, with a promise of $1,000,000 more.[11]

During the 1850's and 1860's, exploration in discovered districts consisted almost wholly of "following the ore." Developments in mining methods and equipment in the 1870's made it possible to follow mineralization to depths previously unattainable, and by 1886 workings had been sunk to depths of over 3,000 feet at the Comstock. These and other developments brought about changes in the types of organizations exploring the districts discovered by the prospectors. It was still true that the individual discoverers did a good deal of initial exploration and development of the veins and other deposits that they found, but often now they formed companies to do the work. In the 1860's the entire Comstock district was developed and continuing exploration performed by companies whose shares were traded on the San Francisco Mining Exchange.

These developments also increased the interest of financiers in investment in Western mines. Agents of many New York, San Francisco, and British financiers travelled throughout the West examining prospects and mines and acquiring the most favorable-looking ones. Thus, a great deal of exploration was carried out in developing districts by corporations controlled by San Francisco, East Coast, and British capital. This situation intensified in the period from 1880 to 1900.

The Eureka district, Nevada, provides an interesting example of the types of organizations involved in exploration of Western mining districts in the last years of the 1870's. The following is abstracted from a paper by W.S. Keyes, superintendent of the Eureka Consolidated Mining Company, read at an American Institute of Mining Engineers meeting in 1877.

> "Silver ore was first discovered in the Eureka District, Nevada, in late 1864 or early 1865 by travellers. The discoverers made some locations and left. Little was done in the district, beyond merely adopting the Reese River mining rules and regulations, until the spring of 1869 when a furnace for reduction of the ores was built. By the fall of 1869, two eastern corporations, the Tannahill Company and the Buttercup Company, had done some work in the district, but both ultimately failed.
>
> "It was in the summer of 1869 that the outcrops of the lodes were found which made Eureka prominent. They were found by Cornish miners two and one-half miles west of the town of Eureka which had sprung up near the original locations. The locators explored and developed their new discoveries. Before long two small furnaces were built to treat the ores. The results were highly encouraging. Subsequently, a party of San Francisco capitalists bought out the owners of the claims and a consolidation was effected with the Buel and Bateman Co. which had built the two furnaces. From the properties thus united resulted the corporation now known as the Eureka Consolidated Mining Co. It was organized in July 1870. During the next few years a large number of corporations

> were formed to work the mines of the district. Among these was the Richmond Mining Company of Nevada, a subsidiary of the Richmond Consolidated Mining Company of London."[12]

An earlier example of the same type of development is provided by the growth of hydraulic gold mining in California. That was also an undertaking too expensive for the lone prospector. The result was the formation of companies to explore and mine the low-grade placers amenable to hydraulic mining.

5. Exploration Costs

While mine development and the deposit evaluation and target area examination phases of exploration were becoming more costly by 1872, the regional reconnaissance phase remained relatively inexpensive. Virtually all mineral reconnaissance in the 1800's was done by prospectors, either on their own account or under a grusbtake agreement. Thus the cost of reconnaissance amounted to the cost of maintaining one or more prospectors and their pack animals in the field. In addition to these costs were the costs of assaying samples of promising outcrops which the prospectors might discover.

Some idea of the cost of provisions and thus the cost of reconnaissance can be obtained from the costs of board in mining towns. At Prescott, Arizona, for example, board could be had for from $16 to $25 per month in the 1870's.[13] Costs were higher in areas where the demand for supplies was great and their supply small due to real isolation and inadequate transportation. In many areas game was abundant, and the prospectors lived off the land, while in others, it was not and complete provisions had to be supplied.

The Sonora Exploring and Mining Company previously mentioned was one exception to the general use of prospectors for reconnaissance. That company employed engineers for reconnaissance, although it may have used prospectors as well. Organized at Cincinnati in 1856, and incorporated under Ohio laws with a two million dollar capitalization in 1857, the company originally committed $100,000 cash to its ventures, and supposedly had promises of a million dollars more.[14] This relatively high budget was established to cover land acquisition as well as exploration and development costs, however.

In the later stages of exploration (district examination and prospect evaluation), engineers were frequently employed. As mentioned, Dr. James Douglas received a fee of $500 in 1880 for a three-day examination of two claims in the Jerome, Arizona, district, and this may have included his travelling expenses from Maricopa Wells to Jerome and back. Dr. Jules Marcon, a geologist who accompanied one of the railroad expeditions west in the 1850's, received $100 per month and expenses.

Deposit evaluation was far more expensive, even in the 1800's. An example of the cost of such exploration projects is the Sutro Tunnel in the Comstock. The tunnel was driven more than 20,000 feet to permit exploration in deep levels of the mines on the Comstock Lode and to permit profitable mining of ore shoots which might be found. From the point of view of exploration, the project was a failure, since shafts had penetrated 1000 feet deeper than the tunnel level by the time the tunnel reached the ore zone. The tunnel did permit more extensive exploration over a five year period following its completion, however, but this exploration did not turn up significant quantities of ore. The cost of the project as given by Richard was $4.5 million, with the actual cost of driving the tunnel amounting to $2.1 million.[15]

6. Principal Minerals Sought

During the period from 1860 to 1880 a real progression is evident in the types of mineral deposits sought in the Western States. This progression was the result of evolving technology, which created new and expanding markets for mineral raw materials, and which made possible production of those materials from previously unassailable ores and ore deposits. This progression took the form of a year-by-year increase in the number and types of deposits of minerals searched for and mined. Its result was the exploration and settling of the West.

The progression really began in 1848 with the simplest precious metal deposits. These were comparatively rich, surface, placer gold deposits. The placers were followed upstream, and the sources of their gold were found in quartz veins. As the higher-grade surface placers were depleted, lower-grade placers came into production. The bonanza silver ores of the Comstock Lode were discovered in 1859. With all of these precious metal deposits, two characteristics were outstanding. First, they were high in metal content, and their richness was easily detectable, usually at the surface. Second, the metals were recoverable by simple metallurgical processes. The deposits paid their way from the grass-roots down.

Exploration for gold and silver deposits in the 1850's and early 1860's resulted in the discovery of prominent outcrops of oxide copper minerals containing significant precious metal values and in the discovery of lead and zinc deposits containing significant quantities of silver. Only enriched, near-surface zones of these deposits were profitably mineable until the coming of the railroads. The railroads brought three immediate benefits to owners of deposits of mixed base and precious metal ores. First, they reduced the cost of transportation of equipment and supplies needed for mining, milling, and smelting the ores. Second, they reduced the cost of marketing the base metal products. Third, they permitted the rapid movement of troops and supplies for the pursuit of hostile Indians. This opened up the last unprospected areas of the West to mineral exploration and permitted the development of mines in areas previously too hazardous for normal mining operations. Base metal production in the West began to increase.

From the outset, the precious metal industry gave rise to exploration for materials needed in its metallurgical processes, such as mercury, copper sulfate, and salt, and for construction materials such as limestone, sand, and gravel. Many other materials were found during the search for gold and silver, and others were recovered as by-products of gold and silver mining during the period prior to 1872. The lists include such commodities as borax, graphite, and antimony.

The development of the mercury industry in the West was directly related to the growth of gold mining. Mercury was used in the amalgamation process for the recovery of finer gold particles from placer deposits and for the recovery of gold from ores of lode mines. The Washoe pan process, developed for treating the silver ores of the Comstock Lode, also used mercury.

The New Almaden deposit was rediscovered in California in 1824, but mining on a significant scale did not begin until 1850. As the gold mining in California industry prospered, heavy exploration for mercury went on. The New Idria deposit, a major discovery, was found in 1853. Exploration expanded northward in the Coast Ranges, and soon important new discoveries were made in Napa, Lake, and Sonoma Counties. During the 1860's, hydraulic gold mining on a grand scale, and operations at the Comstock Lode in Nevada, led to a still greater demand for mercury, and exploration southward from New Almaden led to discoveries in Santa Barbara and San Luis Obispo Counties.[16]

Outside of California, exploration for mercury was probably not as intensive as it was in that state. Mercury deposits were sought in other states, but few of any consequence were found. In 1863 cinnabar was found in eastern Pershing County, Nevada. The mineral was recognized near the center of the state and south of Reno in 1875. Many claims were staked, but through the late 1870's there was only slight production. Quicksilver was discovered in Arizona in the Dome Rock Mountains about 1878, probably during the search for the lodes from which known gold placers were derived. In Oregon, quicksilver deposits were discovered in Douglas County in 1865.[17]

Exploration for limestone deposits began in earnest in California in the early 1850's as a direct result of the gold rush. Beginning in the early 1850's, hundreds of lime kilns sprang up all over California. The rising demand was directly related to the hazardous fires which repeatedly swept through mining towns made of frame buildings. Field stone or brick buildings laid up in mud or in lime mortar became the standard type of construction throughout the gold country. In fact, a great deal of lime had to be imported from Europe to supply demand during the early part of the gold rush period.[18]

Salt was being produced in the San Francisco Bay area in the 1850's. The metallurgical process developed for recovery of silver from the Comstock ores required salt. This not only resulted in increased production in the San Francisco area, but in exploration for salt closer to the Comstock Lode. Salt was discovered in saline playa deposits in Teels Marsh and Rhodes Marsh in Mineral County, Nevada, and was produced from them in the 1860's and 1870's. It was used not only at the Comstock, but in other districts in Nevada as well.

Exploration for other minerals was also encouraged by the metallurgical demands of the Comstock. The most important of the early activities in the Yerington District in Nevada appears to have been the mining of natural "bluestone" (copper sulfate) to supply the reduction works at Virginia City during the period when the great bonanza orebodies of the Comstock Lode were being extracted. The bluestone occurred in the outcrops of the principal orebodies of the Yerington district in considerable quantities. Many thousands of tons were mined to furnish the copper sulfate used in the Washoe process of amalgamating the silver ores of the Comstock Lode.[19]

Nevertheless, before 1872, gold was the most sought-after metal in the West. In the beginning (1848-1849), the type of deposit sought was the rich, surface placer in which gold occurred in the free state and could be recovered from stream gravels by the simplest gravity concentration methods such as panning and sluicing. Bonanza placer gold deposits were discovered in California in 1848. Their discovery led to the rapid exploration of the western territories and the successive development of placer mines in nearly all of them. Exploration for the sources of the gold and the placers began on the heels of discovery of the placers themselves, and both placer and lode deposits were actively sought throughout the West.

During the period before 1872, two major types of silver deposits were sought. In one type, silver (or silver and gold) occurs in ores relatively free of copper, lead, or zinc. An outstanding example of this type is the Comstock Lode in Nevada. In the other type, silver (often with gold) occurs with abundant copper, lead, or zinc, or a combination of these. Antimony and arsenic also are often present in these ores. In both cases, the deposits occurred in solid rock.

Although there was limited exploration for both copper and lead in the West before 1872, such metals were not sought as intensively as gold and silver and those minerals related to their production. The techniques of minerals exploration, as well as the entities and costs involved, were therefore all geared to the search for precious metals. Exploration for industrial mineral commodities, including the base metals, was negligible.

C. CHANGES IN MINERAL EXPLORATION TO 1947

1. Methods and Techniques

Between the 1870's and 1947, the three basic phases of the exploration process remained essentially unchanged, although the objects of exploration, the methods and equipment used, and the nature of the individuals and organizations engaged in the search for minerals did change. In some respects, the changes were great; in others, they were slight.

In the 1800's the non-ferrous base metals became the objects of intensive minerals exploration in the Western States where largely gold and silver had been sought before. In the first half of the 20th Century, deposits of other metals, iron, molybdenum, and other ferrous alloy metals, as well as industrial minerals, were added to the growing list of exploration goals.

Other features of minerals exploration also changed. As the size of useable deposits grew, the average size of target areas increased and the time involved in target examination and deposit evaluation lengthened. Costs also rose as the potential returns from deposit discovery increased and the number of easily found deposits declined.

Some methods of exploration remained virtually unchanged while others were varied drastically to adapt to new types of targets and new equipment. New applications of scientific principles such as magnetism and electrical conductivity as well as new chemical techniques also introduced new procedures into minerals exploration. More advanced methods of excavation also had their effects.

An integral part of prospecting has always been sampling in order to determine the nature, quality, and quantity of the minerals present in a deposit so that an estimate might be made of its economic value. In exploration sampling, change has been gradual for some of the very first methods used still apply. By 1947 the use of test pits was still common if the ground were not too wet and did not tend to cave. Pits were also used for the sampling of dumps. Augers and posthole diggers were still used for sampling soft and low-grade material, such as iron ore, or for sampling piles of tailings. Trenching for cutting through shallow deposits or a tailings pile was also in wide use. Channel sampling by hand, i.e., cutting a shallow channel a few inches wide in an exposed surface of ore, whether underground or on the surface, was likewise still employed at the close of World War II.

A more sophisticated method of sampling brought into operation in the 1880's was core drilling, of which there evolved two kinds, diamond drilling and calyx or shot drilling. These were used for sampling deposits of iron, copper, gold, lead, zinc, salt, slate, gypsum, limestone, and many other minerals where the rock was firm enough to give a good core. Churn drilling had come into widespread use by 1947 for softer ores and often for copper ores, though in the latter case, it was common practice to further check sampling results by other methods. Churn drills were also used, of course, for drilling blast holes in open pit mining operations.

The exploration methods and techniques developed in the period before 1880 were many and varied. They had not been synthesized, however, into a unified body of geologic principles. Thus the disciplines of exploration geology as we know it did not exist, except in a very rudimentary form. In the final two decades of the 19th Century, however, this discipline mushroomed.

In one respect, it was only the applications of geologic techniques that changed out of all recognition, because of the more specialized knowledge of the geologist himself, the greater use of geological maps, and such sophisticated methods as prospecting from the air. At one time, leached outcrops could only be examined by the expensive and slow business of shaft-sinking, whereas by 1947 they could be subjected to chemical and microscopic studies of rock obtained from core samples.

Increasing understanding of geologic processes also helped. It was learned that massive sulfide ores shrink in volume when oxidized, the oxide minerals occupying less space than the sulfide minerals. Discovery of this phenomenon set in motion a search for overlying rock

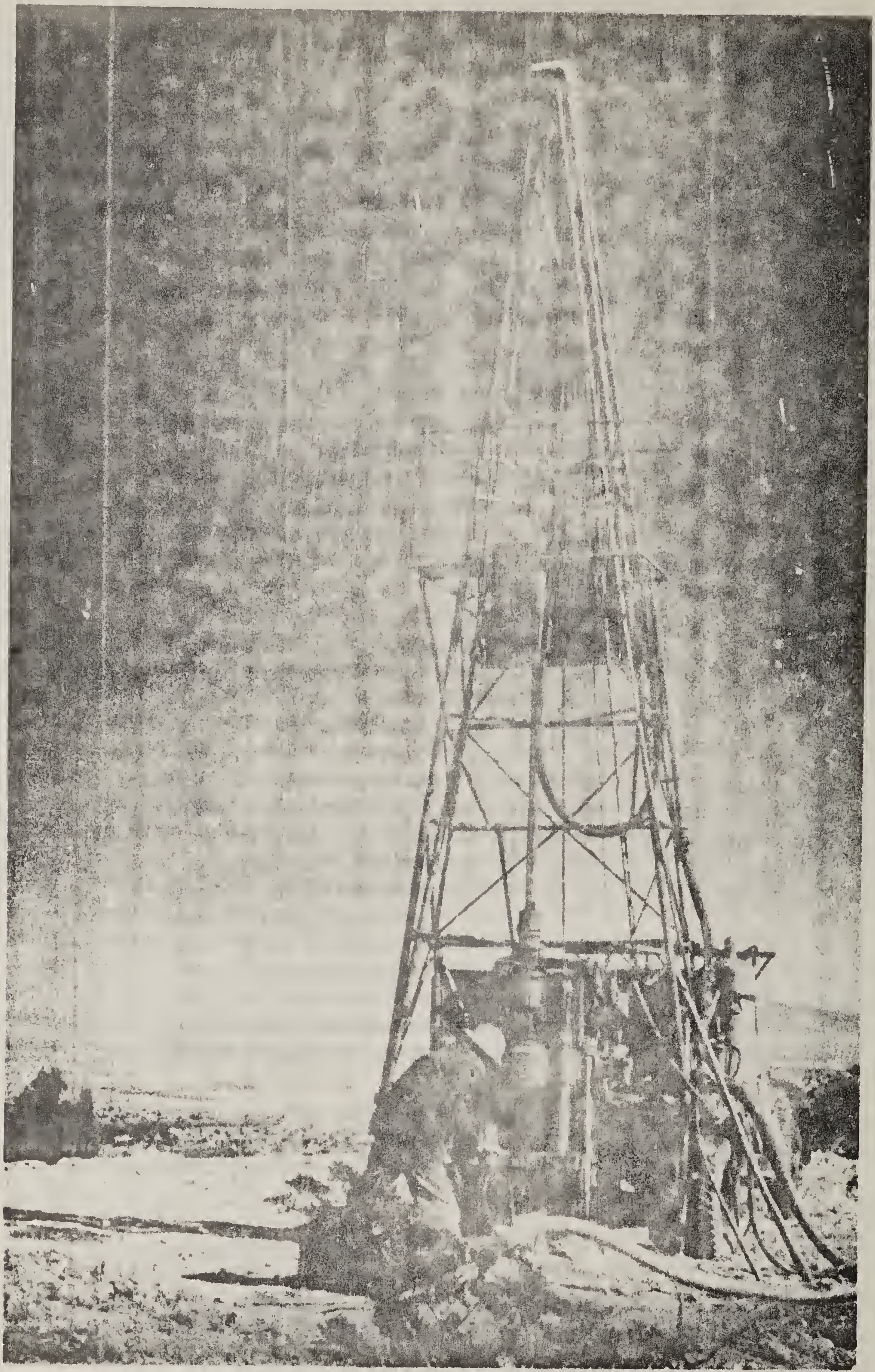


Fig. 4 - The diamond drill was introduced into American minerals exploration in the late 1800's and quickly became an important tool in the testing of mineral deposits. Such equipment as this now provides significant information about subsurface conditions. (Photo courtesy of Thomas Nye.)

cracks. Thus at Bisbee, Arizona, cracks and surface subsidence were studied as indications of the site of new copper sulfide orebodies. A greater awareness, moreover, of the genetic origin of mineral deposits made it possible to ascertain the geological control which had caused minerals to be laid down in a given area. The search for minerals thus became even more the search for the geological feature that had controlled mineral deposition.

There were also other factors that had hardly been accessible to the prospector before 1872. These included a greater understanding of the working of magma and its relationship to intersecting fault zones, plunging anticlines, and other structures. These were traditional in a way, but earned themselves a new significance. By 1947 an eye was still kept open for physiographic guides to new deposits, however. Furthermore, the prospector still looked for mineralogical guides such as an excess of calcium in altered surface flows indicating a possible replacement of bodies of lead ore in the limestone beds below. The plotting of sample results of different minerals occurring together, so that the trend of each might show general trends, became a useful technique. Lithological and stratigraphic guides also remained in wide use.

By 1947, since the main outcrops of most sought-for minerals had already been found and mined, a substantial part of the search for mineral deposits moved from the field to the laboratory. Geochemical prospecting as we know it, the search for and evaluation of geochemical anomalies, areas in which the chemical pattern of selected materials indicates the possible presence of ore, was begun. Although in a sense geochemical prospecting had been used before 1872, by 1947 property most usually measured in establishing the existence of geochemical anomalies was the trace content of some element or group of elements in rock, soil, gossan, glacial debris, vegetation, or stream sediments, which were plotted as dispersion-pattern maps of geochemical data.

There are several other forms of modern exploration which were completely unknown to the prospector of the 1860's but which were developed in the following decades of the 19th Century and during the first half of the 20th Century. Most of these we now class as types of geophysical methods. Geophysical prospecting, of course, in no way became a substitute for geological prospecting, but rather was developed as a supplementary means of locating likely mineral deposits by providing information about hidden structural and mineralogical features so that further exploration by other means might be more effective. The methods of geophysical prospecting developed by 1947 were several, but all were unknown to the early seeker of base and precious metals.

Magnetic prospecting, using a magnetic needle that was free to move in any direction, was one of the earliest of geophysical methods. With the dip needle or magnetometer it became possible to locate magnetite orebodies by measuring their magnetic anomalies. A later development involved the use of a magnetometer towed beneath an airplane while sophisticated equipment in the plane recorded the total magnetic field covered.

Gravitational prospecting using gravimeters, devices measuring the relative attraction of various parts of the earth's crust, were also developed before World War II. But this technique was more often used in exploring for oil and gas than for nonfuel minerals, although it was extremely useful in detecting the presence of salt domes. Seismic prospecting was also more extensively used in oil exploration. In this method the firing of charges of explosives beneath the earth was used to produce longitudinal and transverse vibrations in the ground. The properties of rock between the shock source and the recording instruments could then be ascertained by the velocity with which shock waves traveled through the ground. Electrical prospecting methods were developed, based onthe knowledge that there are differences in electrical conductivity between ore minerals and the enclosing rocks or between adjacent geological formations. Metallic sulfides are especially good conductors of electricity.

By 1947 the importance of radioactive minerals had just been recognized, but this recognition led to still another kind of modern prospecting. The equipment developed to search for these minerals included the geiger counter and the scintillation counter, both of which were sensitive to gamma rays emitted by uranium-bearing rocks.

Thus, while the principles behind prospecting for minerals remained the same, the technology in many respects changed substantially. The minerals seeker still sought an anomaly, but the type of anomaly had changed. To gold colors had been added magnetic, electrical, and radioactive variables. Mineralogical, chemical, and color anomalies, however, still retained their usefulness in minerals exploration. Skilled and trained and equipped with the new technology of diamond drills (already at work in the 1880's), and later with churn drills, and even later with geophysical equipment, the professional engineers to a limited extent superceded the old-time prospector who had evolved his own methods in the hard school of experience. Yet the principles behind those methods were so sound that they have never been completely abandoned, appearing in textbooks of mining written by professional mining geologists and engineers even up to the present. To this extent, the general pattern of prospecting in existence before 1860 did not change, though of course diamond drilling and other modern techniques have proved to be cheaper and more reliable than the old method of putting down trial shafts to estimate the position, size, shape, and value of an orebody.

2. Exploration Entities

But the lone prospector was really replaced only in the deposit evaluation phase of mineral exploration. Prior to 1947, most mining companies had no formal exploration organization. The geology department of a company, under the direction of the chief geologist, normally consisted of resident mine geologists (who also reported directly to their respective mine managers), a few staff and/or research geologists, and a few field men who examined and evaluated mineral properties which came to the attention of the company. Exploration consisted largely of individual prospect examinations by mining geologists and/or engineers. If an initial evaluation report were favorable, physical exploration might be done which might include drilling, surface trenching or pitting, and the driving of underground workings. Reconnaissance and, to a large extent, target area examination were still the primary functions of the lone prospector, even as late as 1947.

Prior to World War II, a large part of a mining company's exploration was normally done by resident geologists in the vicinity of the active mine operations to which they were assigned. New geologists were generally assigned to operating mines to gain experience in the practical aspects of mining geology and in the problems of making and maintaining a mining operation before being allowed to go into exploration work. Many companies had limited geological staffs and relied upon consulting geologists and engineers to examine mineral properties for them. Geophysical exploration, where considered desirable, was done by outside service organizations. A few of the largest companies maintained small regional offices in the Western United States and in several foreign countries (principally in South America) to take care of prospect examinations as they were submitted.

In short, prior to 1947 exploration by most established mining companies was more or less passive. Companies depended almost exclusively upon the individual prospector and small miner to find mineral deposits and at least partially to examine and develop them. These properties were then submitted or came to the attention of the large companies who made their own examinations, further exploring and developing the most attractive-looking properties.

By 1947, however, rising costs, together with a decrease in the number of remaining well-exposed mineral deposits which could be easily and cheaply developed, had made it more difficult for the small miner and prospector to operate successfully. Most of the small, easily-found, high-grade deposits and the large, well-exposed, low-grade deposits located in areas open to exploration and development were in operation or had been mined out and closed down.

SYNOPSIS OF GEOPHYSICAL EXPLORATION METHODS

	Method	Unit	Parameter	Physical Properties	Causes of Anomalies	Major Application
	Magnetic [a,b]	Gamma= 10^{-5} Gauss	Earth Magnetic Field	Magnetic Susceptibility	Basement Rock Irregularities Magnetic Mineral Bodies Mafic Intrusives and Volcanics	Petroleum and mining-general tectonics and local structural patterns Magnetite and pyrrhotite bodies Mafic intrusives with: chromite, nickel, diamonds, hematite Magnetite sand with placer gold
	Gravity	Milligal	Acceleration of Gravity	Density	Dense Orebodies Basement Rock Irregularities Salt Domes	Petroleum and Mining-general tectonics basins, uplifts, and salt domes Chromite, sulfide, and salt bodies
ELECTRICAL	Spontaneous Polarization [a] (self potential)	Millivolt	Natural Potential Field	Conductivity	Conductive Orebodies Graphite Moving groundwater	Petroleum-"electrofiltration" of moving fluids next to drill holes Mining-sulfide bodies and fluids in fault zones
	Resistivity [b]	Ohm/ Meter	Apparent resistivity with applied current	Resistivity or Conductivity	Conductive Orebodies Conductive and resistive strata Fault zones with conductive fluid Salt domes	Petroleum-conductive fluids next to drill holes Petroleum and mining-geologic and tecton tectonics mapping using key beds Conductive orebodies Resistive bodies of: salt, potash limestone limestone, and coal
	Induced Polarization [b]	Millivolt/ Volt	Potential after momentary flow of current	Capacity Effect	Disseminated met-metallic minerals Graphite Serpentine Some clays and micas	Disseminated orebodies, including "porphyry" copper deposits

[a] Includes Airborne Application
[b] Includes Drill Hole Application

Source: W.C. Peters

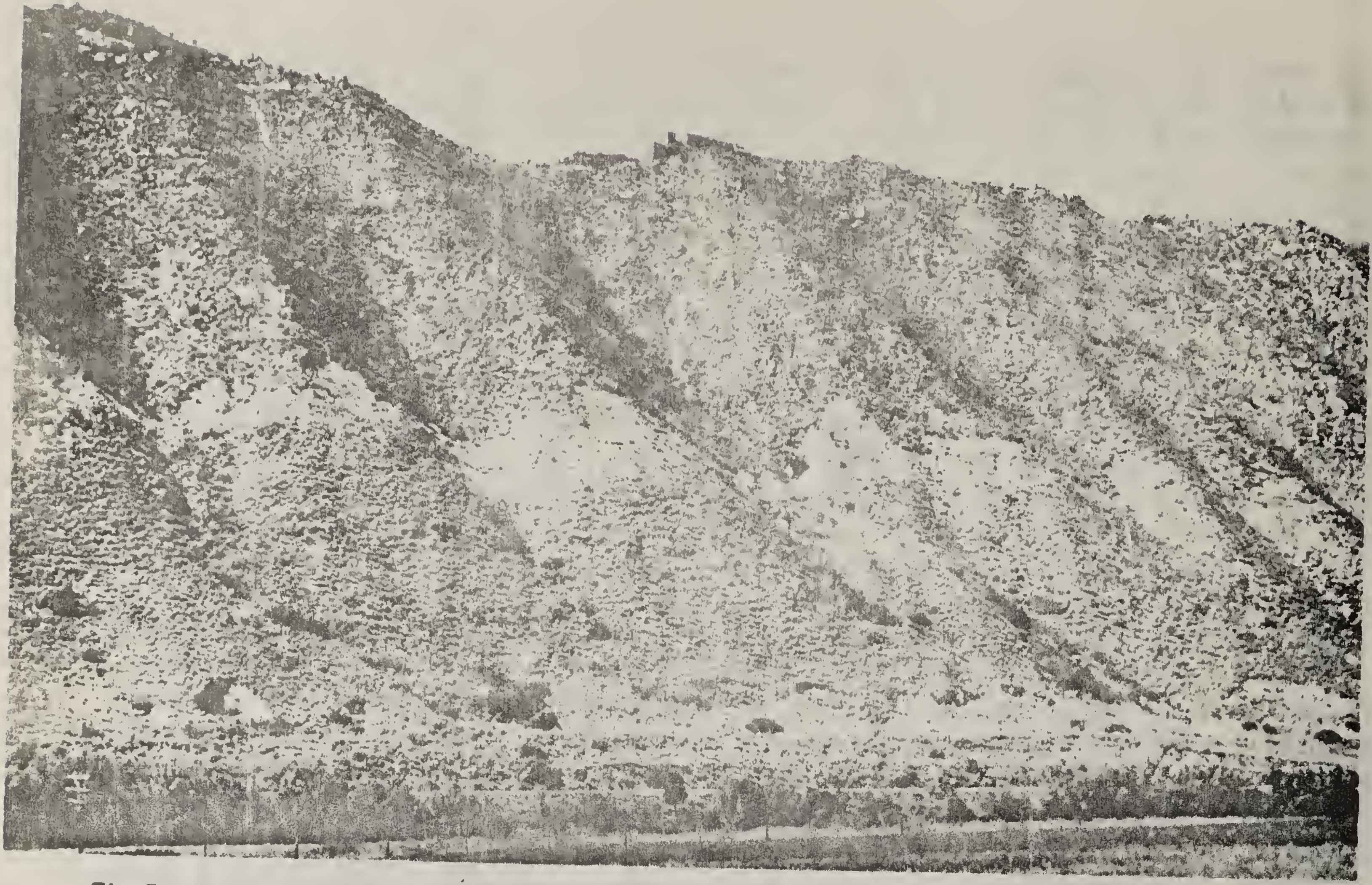


Fig. 5 - Early exploration involved searching for outcrops such as this along the Colorado River in Western Colorado. Surface occurrences of valuable minerals then provided direct evidence of the existence of useable mineral deposits.

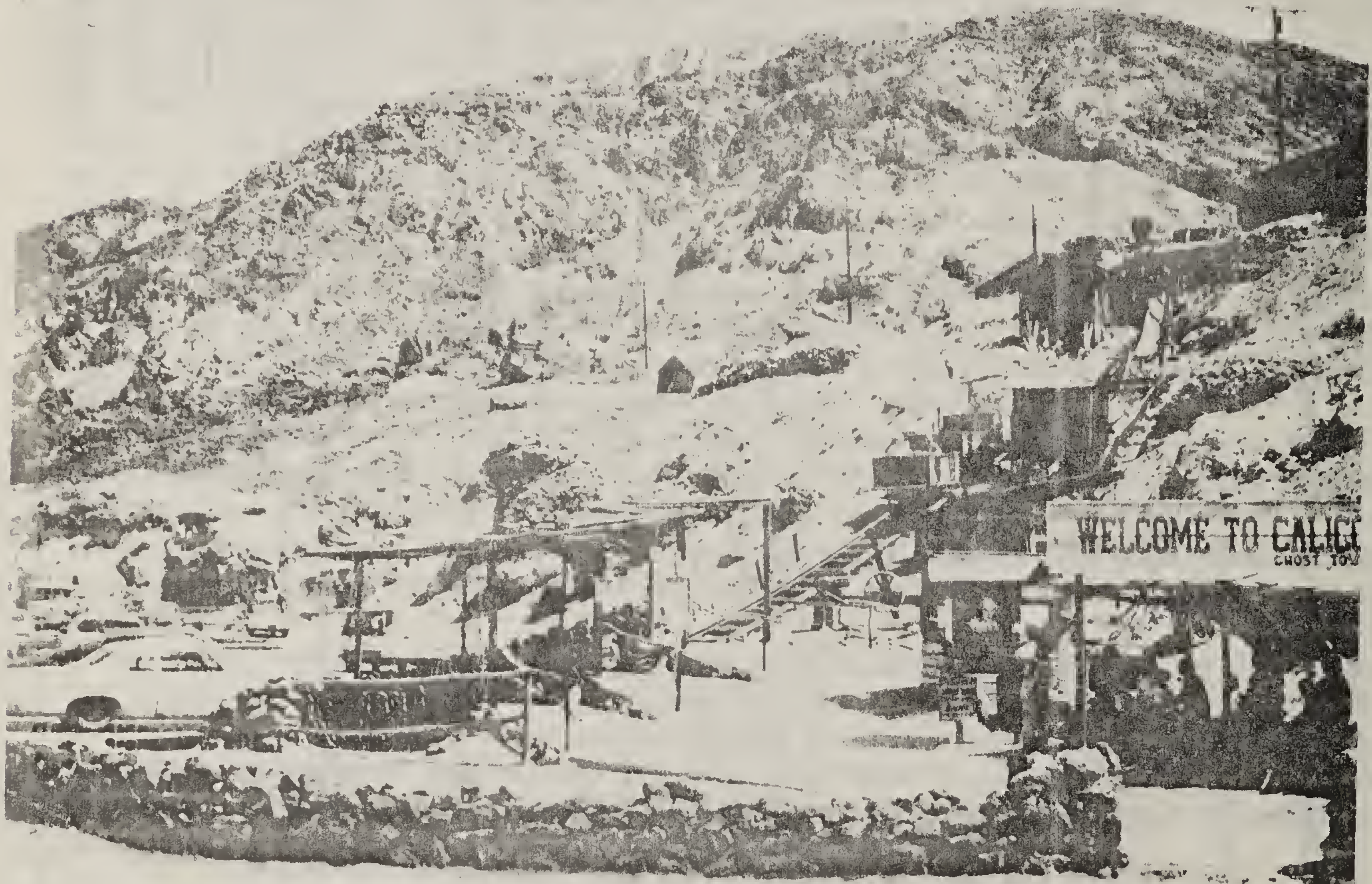


Fig. 6 - Mineralized areas such as this in the arid regions of the West were first worked in the late 1800's when surface and near-surface deposits were explored by individual prospectors using relatively unsophisticated equipment. By 1947, many such areas were no longer active. Revised geologic concepts and new information have since caused a revival of exploration for larger, lower-grade, and less-exposed deposits in just such areas as this.

D. CHANGES IN MINERAL EXPLORATION SINCE 1947

1. Causes of Change

Even with the rapid technological changes that have taken place in the mineral industries since the end of World War II, the basic exploration process has remained essentially the same, involving three principal phases: (1) regional reconnaissance; (2) target area examination; and (3) deposit evaluation. The emphases given to each phase and the various approaches taken have undergone some variation, however.

A number of events have shaped the direction that nonfuel minerals exploration has taken since 1947. The first occurred well before 1947, but it has had a continuing and growing impact on the search for minerals in the United States. This was the beginning of large-scale surface mining of low-grade copper ores from a large disseminated deposit at Bingham Canyon, Utah, in 1906. The recognition of large disseminated mineral deposits as potentially valuable orebodies has had an increasing impact on minerals exploration since 1947.

Two other events somewhat related to the beginning of the Bingham Pit have had a further influence since World War II. The first of these was the development of large trucks and other earth-moving equipment that made disseminated deposits not quite large enough for extensive rail haulage systems workable. The rapid progress made in increasing the efficiency of truck haulage in open pits has made even relatively small disseminated deposits attractive as exploration targets. The second related event was the successful mining by underground caving methods of relatively deep disseminated deposits in Colorado and Arizona. These successes turned attention to deeper, hidden, disseminated deposits as exploration targets.

Another event of more recent occurrence having a significant impact on the objects of minerals exploration is the development of successful leaching methods, particularly in copper production. This has turned exploration efforts to oxides and silicate minerals as well as the sulfides that had been sought between the 1870's and 1940's. Of similar effect was the successful utilization of a laterite nickel deposit in the Pacific Northwest in the mid-1950's, which brought recognition of such deposits as potentially valuable exploration targets.

The achievement of the Newmont Mining Corporation in bringing into production its disseminated gold deposit at Carlin,Nevada, has had a strong influence on the search for precious metals. The rising price of silver has also been of significant importance in influencing the objectives of those engaged in minerals exploration. Of somewhat similar effect as the discovery of the Carlin gold deposits was the discovery of large, low-grade beryllium deposits at Spor Mountain, Utah.

Perhaps the greatest single event in the search for mineral resources in the United States since the end of World War II, however, was the Great Uranium Rush. This activity in the late 1940's and 1950's in many respects paralleled the earlier rushes for precious metals, turned attention to large areas previously considered worthless, used new exploration methods and techniques, and emphasized some of the basic principles of minerals seeking that have been remarkably persistent despite changing economic and technological conditions.

Of a much broader influence in minerals exploration, but not nearly as spectacular as the uranium boom, has been the general shift in population and economic activity to the Western States that has taken place since the end of World War II. This movement has created many new exploration targets in previously unattractive areas and for previously unsought industrial minerals. Of course, the event that has had perhaps the most widespread impact on minerals exploration in the United States since 1947 has been the extensive development of more sophisticated and complex equipment and methods for exploration itself. The progress made in geophysical techniques alone has been substantial.

2. New Geophysical Methods

Unlike the period prior to 1947, direct geological exploration for minerals is now usually supplemented by a study of selected regions or prospects by geophysical and geochemical methods. As the search for mineral wealth has turned more and more to regions of limited or poor rock exposures, geophysical and geochemical methods of prospecting have assumed an increasingly important role. The success of their application is not necessarily contingent upon exposures of the commodity sought. Unlike geological exploration which makes an assessment of mineral potential on the basis of geography, rock type, rock geometry, and mineralogy, the geophysical and geochemical methods now in use employ physical and chemical measurements of certain properties of the rock and soil which may be present over or near a mineral deposit.

As a general rule, areas prospected are now, and have been traditionally, selected on the basis of some favorable geologic characteristic. In those cases where geophysical or geochemical measurements are made, they are commonly, but not invariably, taken in these areas of geologic favorability and are used to help further refine and supplement geologic information. In some instances, geophysical or geochemical measurements may be made in regions where the geology is not clearly known, and in these instances the results of geophysical or geochemical measurements are supplemented by geological studies in order to properly assess the value of the measurement.

The purpose in carrying out chemical and physical studies is to determine the existence and location of anomalies. An anomaly in this context is best described as a physical or chemical property of the crust or its surface that represents a deviation from or contrast with a regional or area average (or a uniform gradient) of that property. A mineral deposit is, by definition, an anomaly.

The assessment of the usefulness and effectiveness of geophysical or geochemical methods has been a difficult task. A characteristic of human nature is a willingness to point with some pride to the success of a program but an unwillingness to discuss failure. The literature abounds with case histories of successes, but the failures so described are few. A failure of an exploration technique could be considered as either the discovery of a mineral deposit that did not respond to the measuring technique or the detection of an anomaly which upon further exploration or development yielded no orebody or economic amounts of a mineral commodity. The success of a technique could be considered as a discovery in which the mineral deposit was measurable by the method used. The success or failure of a particular method does not necessarily reflect the quality of the measurement made, however, but rather the interpretation made of that measurement by man. As interpretive techniques are refined, the success ratios of these newer methods have improved. The same criteria of success and failure apply, of course, to exploration techniques considered to be strictly geological.

Geophysical methods that have been developed and improved since 1947 vary from simple and inexpensively applied techniques to methods involving a great amount of complex equipment, costly application, and sophisticated interpretation of the results. All methods measure a physical property or a contrast in the physical properties of a rock. There are numerous ways in which geophysical methods may be classified and discussed, but the most straightforward is to consider two general types of measurement. The first is the direct measurement of a rock property, such as its relative density, its capacity to enhance, restrict,or otherwise modify the earth's magnetic field, its capacity to transmit or store heat, its polarity, or its behavior in response to natural electromagnetic fields. The second involves the measurement of the response of a rock to some sort of applied energy such as shock or an electrical current.

Measurements of both types are made in the search for mineral deposits. Certain mineral bodies respond more positively to one type of measurement than another, and the search for certain types of mineral deposits therefore commonly involves the use of more than one geophysical method. With the exception of iron ore and radioactive minerals, both of which have properties directly measurable by magnetic and radiometric methods respectively, most types of mineral commodities sought require the interpretation of more than one type of geophysical measurement.

Magnetic measurements are historically the oldest of the methods, and the use of the magnetometer is still widespread today. Its usefulness has been greatly extended through the development of sophisticated sensing instruments, through the use of aircraft and precision navigation systems, and through the use of computers in the reduction of data. The magnetometer's present use extends from a valuable reconnaissance tool to a tool useful in localized detailed surveying of small areas of the surface.

In the search for minerals, magnetic data are used to locate subsurface structures, buried plutons which may be progenitors of metals, and for iron and certain types of deposits of titanium. As indicators of iron ore deposits, magnetic methods are virtually direct indicators, measuring contrasts created by the influence of concentrations of iron minerals upon the earth's magnetic field. In the search for other metals they are used chiefly in conjunction with other geophysical methods and as a tool aiding in subsurface geological interpretations. The costs of magnetic surveys are variable, depending upon the type of survey carried out, but although project costs may be high, the speed of carrying out an aeromagnetic survey and the extensive area coverage that can be obtained have made it one of the least expensive methods used on a per line mile or square mile basis.[20]

Gravity measurements were employed initially in the search for petroleum, but are now commonly carried out to provide supplementary data in the search for metals. The instruments used, gravity meters or gravimeters, are relatively inexpensive and easily operated. Their great sensitivity allows determination of extremely small variations in the earth's gravitational attractions. These variations are interpreted in terms of the contrasting densities of adjoining rock bodies and thus may be used to locate and analyze the characteristics of buried plutons, bodies of iron ore, or massive sulfides. Gravity data are also useful in aiding in subsurface geological interpretation of important localizing structures.

Gravity measurements are usually made on the ground but require more ground control than do magnetic ground instruments. In the search for metals, the gravimeter is seldom used as a reconnaissance tool to the degree that a magnetometer may be. The method has been used as an exploration tool in searching for metallic ores from underground workings.[21]

The use of natural audio-frequency magnetic fields in the search for metallic deposits is a comparatively new method in geophysical exploration. The technique involves measuring the distortion of natural electromagnetic fields by electrical conductors. The method is especially suited to exploration for continuous electrical conductors such as veins or massive sulfide deposits. The method is inexpensively applied, requiring only a receiving and orienting device. As it has been in use but a short time, it is difficult to make any assessment of its potential other than to reiterate one authority's statement that "Clearly more field, experimental, and theoretical study is needed."[22]

A metallic sulfide deposit situated near the surface of the earth undergoes chemical changes as the result of the action of water and oxygen. These changes set up weak electrical currents which may be directly measured. The self-potential method, in comparatively crude fashion, has been of use in evaluating and outlining such sulfide bodies near the surface. In recent years it has been made a bit more elaborate and is not used routinely in conjunction with more advanced electrical prospecting techniques. There are few known discoveries that have been made by the self-potential method alone, but it is a method that has been used rather widely in connection with other types of geophysical measurements.[23]

The direct geophysical methods described are those in common use today and those in which research is being carried out with a view to further refining their usefulness. The magnetometer and the gravimeter are now utilized in both ore search and mapping, and the other methods are used chiefly in ore search. These methods can now be applied at low cost and have provided useful information in the search for and the mapping of mineral deposits.

With continued refinements of instrumentation and with the application of computers to the solution and interpretation of the data, these methods will continue to be used in the search for valuable mineral deposits.

In response measurements methods, two types of energy are applied to the crust in order to measure different types of rock response. One of these is shock, applied either by explosives or the dropping of heavy objects (thumpers) on the surface. The shock moves through the crust in ways which are governed by the nature of the rocks traversed. The characteristics of the shock waves which reach a receiving station are recorded and studied.

The other type of energy is electrical energy which is applied either as an electromagnetic field or as direct or alternating electric current. The resultant response of the subsurface to the applied electrical energy may then be interpreted indirectly or directly in terms of a potential mineral deposit. The method depends upon a contrast within the subsurface of rock conductivities or capacities to act as a condenser in storing and discharging electrical current.

Alternating current flowing through a wire or group of wires sets up its own electromagnetic field. If a conductor is brought into this electromagnetic field, the conductor establishes its own electromagnetic field by a process known as induction. The nature of this induced electromagnetic field is a function of the geometry and resistivity of the conductor.

This electrical principle is utilized in geophysical exploration by setting up fixed or movable electromagnetic field sources and measuring the response of the subsurface material to the field by means of a moving receiver. There are actually a great many ways in which the same principle is used that include a straight wire in a fixed position, movable multi-wire loops, and numerous types of source-receiver geometry. The method has also been adapted with considerable success to aircraft which carry both sources and receiver and are able to produce data that are interpretable in terms of maps of conductivity contrasts of the near subsurface.

Since climate produces soils of varying conductivity contrasts, the effectiveness of electromagnetic methods has been more restricted geographically than most other geophysical methods, and it is not of as widespread use in the desert regions of North America as in the more temperate and arctic regions. Electromagnetic methods are most usefully employed in the search for orebodies composed of continuous conductors such as sulfide veins. They have not, historically, been of much use in the search for dispersed conductors such as disseminated copper in igneous intrusions. There are, however, recent developments in the methods which suggest that dispersed conductors will respond to appropriately applied electromagnetic fields and that the responses are measurable and interpretable.

Since all that is needed for response to the electromagnetic induction is a continuous conductor, the responses seen in electromagnetic geophysical methods may not always be that of metallic-sulfide deposits. The method detects, with not too much discrimination, veins of graphite and water-filled veins. In both airborne and surface-applied techniques, it seems likely that the shallowly buried veinlike deposits of both Canada and the Northeastern and Northwestern United States will continue to be discovered by this method. The cost of application is about as variable as magnetometer studies. Simple, inexpensive, but effective portable field units are cheaply run in surface studies, and the use of an aircraft provides information useful in mapping. As with the magnetometer, total job costs are high with airborne work, but the per-line-mile or per-area costs are relatively low.

By applying either a direct or alternating current to the ground, applied potential measurements may be taken that are either directly or indirectly useful in the mapping of the subsurface and in the search for hidden metal deposits. As with all of the methods described, the applicability of any applied potential method is dependent upon the existence of a contrast, in this case, a contrast in the electrical properties of the subsurface materials. Although there are many variations of current applications and measurement techniques, one type of measurement is now made on a widespread scale using the technique of induced polarization.

Induced polarization takes advantage of a characteristic of minerals in which they behave like condensors. If a large potential is applied to the ground and if there is a dispersed or continuous conductor present, the metallic grains behave as though they are small condensers, and build up a charge on the surface. If the current is chopped (stopped), the "condensers" decay and the resulting voltages together with their variations with time are measurable. This method is especially useful in the search for any type of dispersed metallic mineralization. There are many variations of this method now in use and the method has been used successfully in the search for dispersed metals.[24] Cost of the application of this method is somewhat higher than many other techniques and, depending upon electrode configuration, may range in cost from $150 to $600 per line mile of traverse.[25]

Another useful application of the applied potential method is the study of subsurface resistivities. By applying a potential to the ground and studying potential drop, resistance of the ground can be measured. By varying the electrode spacing, layering of the subsurface, if accompanied by resistivity changes, can be determined with proper interpretation. The method is therefore useful in mapping. If a continuous conductor (say a metallic orebody) of sufficient size is within range of the power used, it can be detected. Portable equipment is available to carry out resistivity studies, and the method is relatively cheaply applied.[26]

Long used as a major tool in the subsurface mapping of and search for petroleum reserves, seismic methods also have begun to play a role in the search for metallic mineral deposits. Their chief application is in the determination of overburden thicknesses above mineral deposits, and in this application seismic techniques have been used in the North-Central and Southwestern United States.[27] The relatively shallow seismic work carried out in mining exploration is comparatively easy and inexpensive. As used in petroleum seismic work, the shock source usually consists of explosives, detonated in a hole drilled for that purpose. The measurement of the shock velocity in rock is made by means of detectors set out over miles of line. More recently, shock sources which are nothing more than heavy weights dropped on the ground have come into use. In nonfuel minerals exploration, the depths studied are shallow by comparison with petroleum work, and the sources of shock needed are thus of lower energy. For some methods, the shock source is provided by striking the surface with a sledge hammer. As with the other geophysical methods, the degree of sophistication largely determines the cost. The seismic studies carried out in the search for metals are generally at the low end of the cost scale.

Applied energy geophysical methods tend on the whole to be a bit more complex than direct methods because of the requirement of an energy source. Nevertheless, they have been devised to determine some value or discrete set of values of rock properties and can be modified to test a spectrum of properties that vary with the nature of the applied energy. As a consequence, they tend to cost more in their surveying, and are not considered mapping tools.

3. Geochemical Exploration Methods

Unlike most geophysical methods, which measure a physical property or response of a rock to excitation, geochemical methods make a direct measurement of the composition of a natural material in order to determine the nature and amount of an element or elements present. Geochemical prospecting is a technique that attempts to locate anomalous conditions of chemical composition. The approach to geochemical studies can be considered two-fold. There are methods useful in reconnaissance and methods useful in detailed target area examination and in supplementing geological or geophysical information.

The existence of geographic regions in which certain metals are relatively more abundant than in others is a matter of fact. These regions, such as the copper province of the Southwest or the lead-zinc province of the Mississippi Valley, are characterized by trace element contents of these respective metals as well as certain associated metals that are higher than corresponding contents of these metals in rocks or soils outside of the province.

Reconnaissance methods are useful in locating and defining other provinces unknown to man. Within a metal province, such as the Mississippi Valley, reconnaissance methods are useful in outlining smaller exploration target areas.

Climate has a major influence upon the way in which metals are deposited, and therefore, different reconnaissance methods are used in different regions. In temperate and alpine regions where stream flow is nearly continuous, studies of metal content of water or stream sediments are commonly carried out. In arctic regions, the study of stream sediments and waters is useful in those seasons when possible, and the study of material in the debris pushed by glaciers has also been fruitful.[28] Reconnaissance prospecting in dry areas (exclusive of the Arctic) relies upon other characteristics of geochemical behavior. The evaluation of the trace element content of vegetation is a commonly used method as is the study of well water. The study of sediments in intermittent streams has been carried out, but with unevaluated success.

In virtually all climates, soils are analyzed in geochemical reconnaissance, but each geological environment presents its own special problems in the use and interpretation of geochemical data so derived.[29] Soils can be considered of two extreme types in their development–residual or transported. Residual soils dominate in regions of comparative geologic quiescence such as the Mississippi Valley, and transported soils are the dominant product of more active weathering environments such as the desert Southwest. In residual soils, metals derived from underlying rocks tend to be comparatively immobile and reflect the manner in which soils are drained. Transported soils, on the other hand, do not "mature" in place and as a consequence, metals which may be derived from the underlying rocks do not concentrate as readily as in the residual soils. Exceptions to either case, however, are not unusual, and reconnaissance methods utilizing soils require considerable study in their interpretation.[30]

Seldom applied usefully as the principal method of ore search, geochemical prospecting is commonly employed in conjunction with other prospecting techniques that include geology and geophysics. There are reports of a few attempts to use the method as a primary tool of exploration, but the success attained has been questionable. There is considerable variation in the detail of application of the method, but generally speaking, an analysis is made of rock, soil, vegetation, minerals, stream or lake water or other natural material to determine the level of concentration of trace amounts of metals present in parts per million or even per billion. The analyses are made accurately, swiftly, and cheaply in most instances. The slow step in the process of this type of exploration is simply that of travel to and from each sample site.

Although certain geochemical observations have been made by man for centuries, the style and type of prospecting now in use in the United States dates from about 1946 and virtually all significant advances in the method have been made since World War II. The general trend of advance in geochemical research has been in several aspects of the method. There have been advances in speed, simplicity, accuracy of analysis, and in methods of interpretation. In the early years of the use of geochemical prospecting in this country, virtually all analyses were made of material returned to a laboratory. In order to speed the work, several research organizations, both public and private, have developed field kits that may be carried to the sample site, allowing the determinations of trace element content of rock or soils on site. Because certain natural materials such as stream and well water, for example, contain such low levels of metal concentration, extremely sensitive tests for the metals sought have been developed in order to use these materials in the search for hidden deposits.

Sophisticated geochemical interpretive techniques have evolved through the use of computer programs that analyze and develop statistical maps of the data. Nevertheless, the interpretation of data probably stands now as one of the most serious problems in the application of this method.[31] A large number of metals are present in any soil and may be analyzed. The problem, however, is to determine what value of a given metal is significant and indicative of anomalous conditions. Thus the problem is to resolve the "signal" out of the background "noise" or "static" and to determine how much metal is significant, i.e., how "loud" the signal is.

If a region is selected as being favorable to mineralization by an exploration technique involving either geology, geophysics ogeology, geophysics or geochemistry, geochemical prospecting techniques are commonly applied to detail the nature of metal dispersion within it. Such methods, in contrast to regional reconnaissance techniques which evaluate widely spaced samples, involve the study of closely spaced samples of soils, rock, minerals, or vegetation. Once a target is located by some means, it can sometimes be narrowed by these methods, and often by repetitious but finer applications of the same method.

The study of complete soil profiles gives useful information, as does the study of metal content in certain vegetation types.[32] Detailed study of alteration minerals, an aspect of geochemical prospecting in which actual minerals are studied and mapped, has assisted in outlining mineral deposits. In addition to the minerals themselves, studies of their trace element chemistry are commonly useful, as is the study of the trace element contents of the oxidation products left in the destruction of metal deposits.

As a reflection of the developments that have taken place in both geophysical and geochemical exploration methods since 1947, an increasing number of mineral deposits have been found by such means. In Canada one-third of the significant non-ferrous metallic mineral deposits discovered since 1950 were found by geophysical methods. Only one of 75 new deposits was found through geochemistry, however.[33]

4. Commodity Variations

The modern techniques of minerals exploration that have been developed since 1947 are, of course, not uniformly applicable in the search for all minerals. It is a geologic truth that different types of mineral deposits characteristically occur in different environments of rock association and structure. Metallic mineral deposits, for example, are most commonly found in areas which have been intruded by igneous rocks. Such deposits may occur within the igneous rocks themselves or in other rock types in close proximity to the igneous intrusion. Some metallic mineral deposits (e.g., iron oxides) are often located far from any known igneous rocks, and theories of their origin have been the subject of considerable debate. Potash and borate deposits, on the other hand, are normally found in areas where sea or fresh water has been trapped in lagoons or lakes and subsequently evaporated.

Many elements and minerals occur in more than one environment of rock association and structure. Some mineral deposits (e.g., magnesite) may have originated from either sedimentary processes or intrusive igneous and/or hot spring activity. The accompanying table shows the applicable geophysical and geochemical techniques typically used in exploration for various minerals. Antimony, arsenic, and bismuth are commonly associated with other metallic mineral deposits and are not generally sought separately. Vanadium occurs in many uranium deposits, so that techniques used in uranium exploration in effect apply to vanadium also. Certain metals, however, are sought primarily as indicators of the presence of other minerals. Arsenic, for example, may be sought as an indicator for tungsten but not for itself.

Geophysical techniques are used in exploration for most metallic mineral deposits and for sulfur and evaporite deposits. Geochemical techniques are used primarily for non-ferrous base and precious metal deposits, as well as those of molybdenum and nickel. The detection of natural or induced radioactivity is used in the search for uranium, thorium, and beryllium. Instruments which measure variations in radioactivity are also used to detect evaporite and sulfur deposits, which are characteristically lower in radioactivity than their surrounding rocks. Salt domes, with or without associated sulfur deposits, are generally less dense than the surrounding rocks and can therefore be detected by relative gravity measurements.

Exploration for metallic mineral deposits (except large iron and manganese sedimentary deposits) generally involves more detailed procedures of study, a greater physical collection of data (mapping, geochemical sampling, geophysical surveys, drilling), and more intensive

Table 3

MINERAL DEPOSITS FOR WHICH GEOCHEMICAL AND GEOPHYSICAL METHODS OF EXPLORATION ARE USED

A. METALLIC MINERALS

1. *Exploration by both geophysical* (magnetics, gravity, electrical) *and geochemical methods* (sulfide minerals and native metals associated with sulfides)

   Gold, Silver
   Copper, Lead, Zinc
   Nickel, Molybdenum
   Cobalt

2. *Primary geochemical exploration*

   Gold, Silver
   Mercury

3. *Exploration primarily by geophysical* (magnetics, gravity) *methods* (oxide minerals)

   Iron
   Chromium
   Titanium

4. *Fluorescence by ultraviolet light*

   Tungsten
   Zinc (rarely)

5. *Nuclear detection devices using natural or induced radioactivity*

   Uranium, Thorium
   Beryllium

B. NONMETALLIC MINERALS

1. *Electrical and radioactive well logging*

   Saline and evaporite deposits

2. *Radioactive, magnetic, electrical, and gravity geophysical methods*

   Sulfur

Source: E. Wisser and Associates

evaluation than is necessary for other types of deposits. Typical of the exploration for metallic sulfides is the recent program followed by one major mining company engaged in exploration for copper and molybdenum in Arizona. This firm began with air reconnaissance, looking for areas of bleached rock or the red rock capping high in iron oxides that is commonly associated with deposits of these metals. Once located, these color anomalies were checked by geochemical traverses using broadly spaced (500-1,000 feet) sample collection points. In conjunction with this, geochemical samples were collected from stream sands of major tributaries draining mountainous regions at intervals of a mile or more.

The combination of color anomaly and anomalous geochemical samples prompted a decision to explore one particular area in greater detail, although it was in relatively inaccessible terrain. Based on the aerial and chemical data, claims were first staked over the ground in question, and in the process the pre-existing claims of a small prospector-miner were found to cover part of the area of greatest interest. A lease with option agreement was made with the owner for his claims. A local rancher, who had grazing rights to the surface in the area, was reassured of the company's intention to cooperate with him to the fullest extent so as to avoid any damage or disruption of his ranching operations. Friendly relations were established and maintained during the entire project.

Detailed geologic mapping (at a scale of 100 feet to the inch) and geochemical sampling (at intervals of 100 feet) of more than three square miles were done, using a measuring tape and Brunton compass as surveying instruments. Features recorded in the mapping program included the extent, intensity, and type of rock alteration. (In areas of known copper and molybdenum deposits, the enclosing rocks are generally partly or completely altered to clay, mica, and quartz.) Also recorded were the distribution and abundance of iron oxides and iron sulfides, and any copper and molybdenum minerals, as well as the orientation and intensity of fractures and faults, and the distribution of specific rock types. Underground workings on the small miner's claims were mapped and sampled. Rock specimens were sent off for x-ray and microscopic analysis, and the determination of minerals present. In the meantime, the claims which had been staked were properly monumented and surveyed as were those belonging to the small miner. Courthouse records were checked for any additional claims or private land in the area, and verification was made of the title of known land holdings.

The data collected were then plotted on maps and analyzed. Aerial photographs were used to construct the map base upon which the geologic and geochemical data were plotted, as there were no existing topographic maps of the area. The principal target area was evident from the data plotted and was outlined for testing by drilling. Roads were constructed and drill sites prepared. Ten holes were diamond drilled, but the core showed inconclusive or negative results, and the project was subsequently abandoned.

More than six months were required from the time the decision to explore the target area in detail was made to the time that the first drill hole was put down in the specific target. The total time spent in the reconnaissance and detailed exploration of this one area, including drilling, exceeded two years. At various stages of the project from three to ten men were at work on it, exclusive of those involved in the drilling, which was performed by a drilling subcontractor. Had the extent and grade of mineralization proved large enough after this initial exploration to warrant further drilling, at least one and possibly two more years and the drilling of from 20 to 50 holes would have been required to demonstrate the existence of a mineral deposit. The gathering of sufficient data to demonstrate the existence of an economically useable mineral deposit, the third phase of drilling, would have required even more time and drill holes. Upon abandonment of the project, the geologic and assay data collected by the company on the small miner's holdings were turned over to him.

By way of contrast to the type of effort that has come to be involved in the search for metallic minerals is the example of a major chemical company that decided to become a producer of natural sodium carbonate (trona). Following an office study of published geologic information and open file reports from various government agencies, a target area in Wyoming was selected and several public land survey sections were leased from the government. The projection of known individual rock formations and inferences about their thickness indicated a likely area for the location of trona beds of suitable thickness. Several exploratory holes were drilled at widely-spaced intervals and confirmed the presence of an adequate thickness and purity of trona. The mineral-bearing rock formation was projected between drill holes, correlated with assay data, and ore reserves were calculated.

Many non-metallic mineral deposits in sedimentary rocks are relatively large, more or less flat-lying, and form targets which are easy to explore with the use of a minimum of drilling, mapping, and other exploration methods. Access is not usually difficult as the targets generally occur in plains areas, and much of the exploration process can be done by office studies of published information and open file information from various federal and state agencies. There are exceptions, of course. The Western phosphate deposits are highly folded and faulted, and are located in mountainous terrain, making the tracing of phosphate zones and the selecting of areas favorable for mining difficult.

Exploration for valuable mineral deposits associated with metamorphic rocks is quite variable in the amount of detailed work and the development of regional data required. Some clues are usually available from published information, but both broad and thorough reconnaissance of potential target areas is a necessity. This must be coupled in many instances with reconnaissance mapping to narrow down or point to specific target areas. A varying amount of detailed mapping may be required, depending upon the abundance of outcrops of the mineral sought and the complexity of associated rock types and geologic structure. Deposits of this type are often in mountainous, relatively inaccessible terrain.

Valuable mineral deposits associated with the igneous formations known as pegmatites are normally explored by locating areas (largely through library research) where these rocks are known or are likely to occur. These areas are then narrowed down to those likely to contain pegmatites carrying the desired minerals. The most attractive areas are then examined on the ground. Favorable appearing pegmatites are then mapped in detail, sampled, and drilled to determine the amount and grade of the desired minerals.

Deposits of minerals and rocks used in construction, such as limestone, gypsum, sand and gravel, crushed rock, dimension stone, pumice, and expandable shale, must generally be located relatively near a market area because of their low value to weight ratio and high transportation costs. When particular deposits do not occur in close proximity to a local market they may be transported for moderate distances, however. Exploration for such minerals consequently spreads outward from a local using area. The value of the particular mineral commodity is based on its physical characteristics (e.g., color, texture, size of particles or pieces, as in flagstone) and chemical behavior (e.g., reactivity or non-reactivity of sand and gravel with cement).

Specifications for sand and gravel in different uses have become exacting. The ratio of sand, clay, and gravel, as well as the type of contained rocks (the rock in some sand and gravel deposits is not sufficiently resistant chemically or physically to be used) and the amount of overburden to be removed, all affect the value of sand and gravel deposits. If the ratio of sand and clay to gravel is too high the deposit may not be valuable as a gravel source.

Exploration for such industrial minerals deposits is done by scouting the area outward from a specific market, looking in appropriate geologic environments for deposits occurring at or near the surface. If a deposit is found that looks as though it can be acquired and mined without too much difficulty, the area is secured and drilled, trenched, and sampled. Samples are subjected to physical and chemical tests to see if products made from the deposit will meet marketing specifications. If the results are favorable, studies of mining, manufacturing, and marketing feasibility are made. One of the essential keys to success or failure from this point on is not really the location of the deposit but the ability of the producer to penetrate and satisfy the target market. Actual production and marketing rather than theoretical determinations of the marketability of the product, therefore, determine whether such an industrial mineral deposit is ore or waste at any given time. This type of mineral exploration has become increasingly important since 1947, particularly with the growth of population in the Western States and the increasing urbanization of the entire nation.

5. Exploration Entities

The depletion of known ore reserves, an increasing demand for raw materials, the disappearance of well-exposed mineral deposits on accessible land, the active discouragement of the small prospector-miner as an exploration and development tool, and the generally reduced availability of mineral-bearing lands after 1947 caused an explosive expansion of exploration by operating mining companies. Most of this expansion has occurred in the years since the end of the Korean War. Many companies have established formal exploration units which, in some cases, are relatively autonomous divisions or even subsidiary companies. The exploration manager or vice-president and the president of a subsidiary exploration company now typically rank higher than the company's chief geologist. The attached charts illustrate some of the recent exploration organizations used by some of the larger mining companies. This trend to formal exploration units has extended to the smaller companies as well. For example, the Callahan Mining Company established an exploration group under a vice-president in charge of mining and exploration in 1964. Three regional offices were set up, with formal exploration policies and goals.

Minerals exploration by mining firms has shifted from passive to aggressive, through necessity. By 1960 the companies no longer had a large backlog of properties partly explored and developed by the small prospector-miner, and exploration emphasis was shifted to the active reconnaissance of large regions and the examination of known mining districts for larger, less-exposed mineral deposits. Regional and district offices were established from which active exploration could be conducted. Local offices were set up in particularly active areas, under regional offices. Research staff organizations were formed to assist these offices with in-depth studies of areas and concepts favorable to the search for ore. Geophysical and geochemical service organizations sprang up and were gradually supplemented and supplanted by the establishment of geophysical and geochemical units within company exploration divisions. Specialists in particular forms of exploration and in particular mineral commodities were trained or added to exploration organizations. Land men and land departments were formed to deal exclusively in land problems and acquisitions.

Geophysical and geochemical exploration and land acquisition at one time were (and still are, in many of the smaller companies) largely handled by geologists. As the size of the minerals exploration effort grew, these functions became too specialized and burdensome for the individual geologists to handle in addition to their other exploration responsibilities. Just as geophysicists and geologists specializing in geochemistry were added to the organizations as service personnel, so also the multiplicity of land negotiations and acquisitions coupled with the need to check the status of various state, federal, and private lands for previous claims and titles became a full-time job for one or more men.

Since 1947, the exploration units of nearly all of the principal mining firms have grown in size and complexity. The organizational patterns shown in Figures 5 and 6 are typical of the organizational structures that have evolved in the exploration activities of large minerals firms since the end of World War II. In the first, the new exploration specialists were simply added to or fitted in with the existing mining organization. In the other, exploration was given special emphasis with the creation of a subsidiary company designed solely to search for new mineral deposits and evaluate existing properties.

6. Types of Deposits Sought

One of the conditions that has accompanied the growing complexity of minerals exploration, and in fact contributed to it, is the rapid disappearance (particularly since

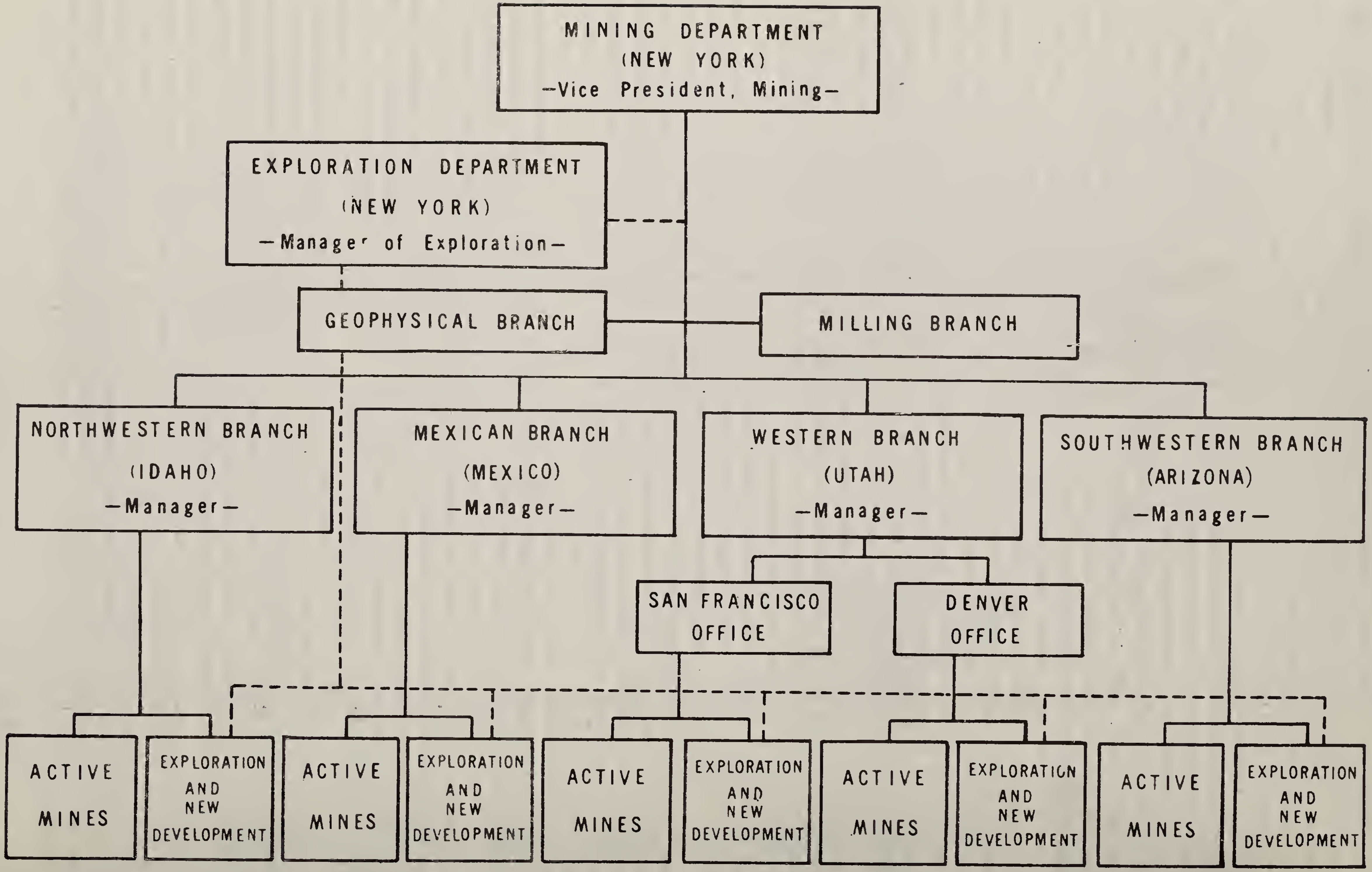


Fig. 7 - Organization of a large non-ferrous metals mining and smelting firm with exploration activities mingled with the production organization.

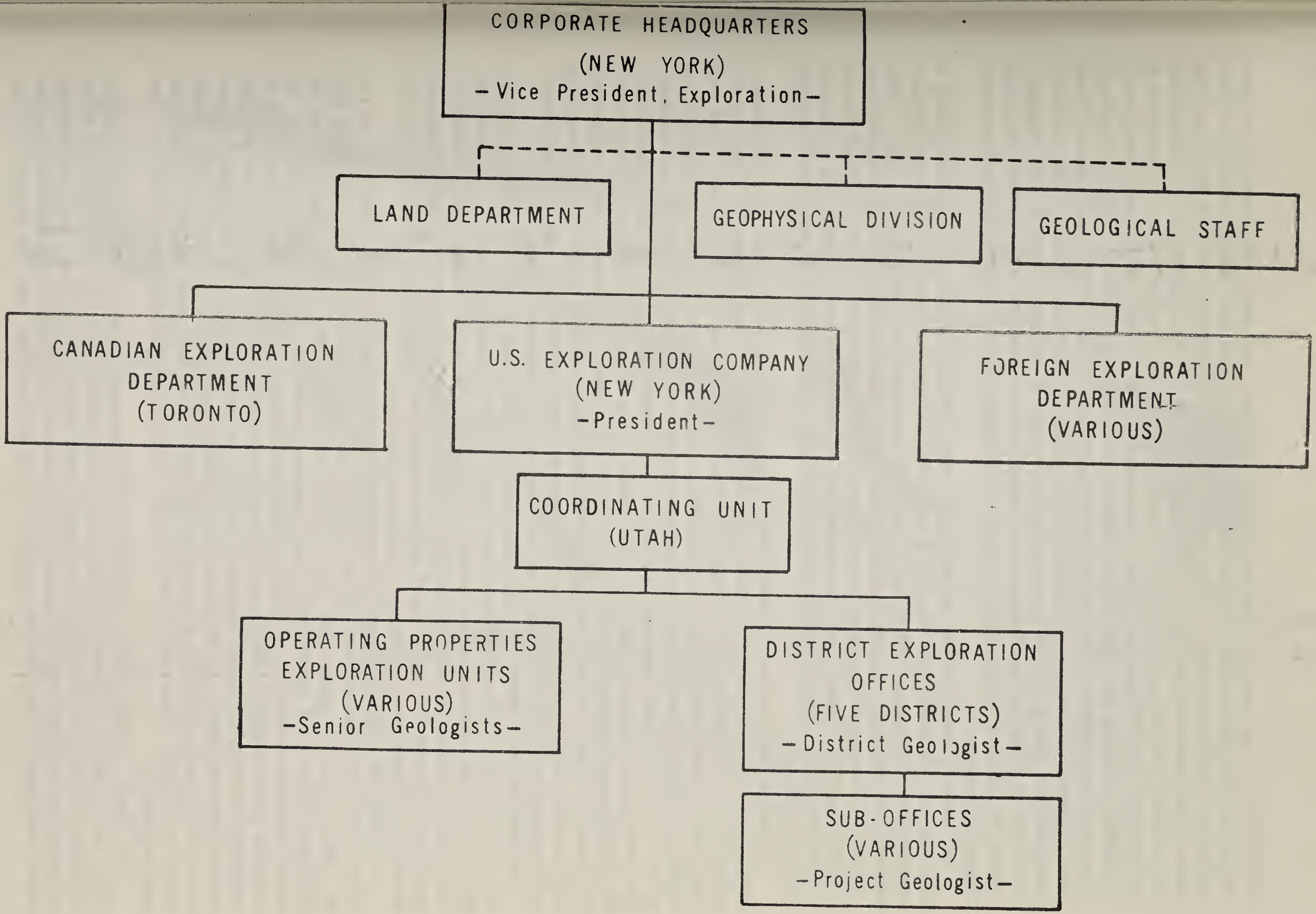


Fig. 8 - Organization of the exploration organization of a large non-ferrous metals mining company using a separate subsidiary company solely responsible for minerals exploration.

World War II) of outcrop mineral deposits and the increasing importance of hidden orebodies. This has been so even in established mining districts, where the need for new orebodies to replace those depleted by the high minerals production of World War II and the Korean War has been particularly acute since the late 1940's. Concepts have changed and the methods have improved, but the sequence of events leading to the discovery of a concealed orebody follows an old and often-stated pattern. It begins with the recognition of a favorable situation and with the formulation of logical supposition for testing. A series of alternative suppositions, investigations, newer suppositions, and closer investigations follow until a discovery is made or until further investigation cannot be justified. The favorable geological situation is the all-important anchor point. In a broad sense, it is an anomaly, some item of potential significance which stands above a threshold value and which can be recognized against a background of "normal" geological, geochemical, geophysical, or other relevant conditions.

An anomaly may involve an apparent concentration of known orebodies along a particular structural zone or "break." It may refer to the geochemical association of certain metals with a sedimentary bed, or it may be expressed as a geophysical "high." Two prospect pits exposing the same fracture zone suggest a favorable situation and represent no less of an anomaly for geologic investigation than a conductive zone indicated by an electrical survey. In either case, the recognition of an anomaly requires searching effort and skill in recognition. Both searching and skill require a committment of money and men for an extended time.

A great majority of ore deposits, even those discovered in the classic days of surface prospecting, were concealed in some way during most of their history. In order to be recognized at the surface, an orebody must have been exposed so quickly that it did not have time to attain equilibrium with the surface environment. Rapid erosion, a landslide, or a railroad cut have in many cases achieved the purpose of "catching an orebody by surprise" while it was still a visible anomaly and before it had decomposed enough to be concealed in the immediate geologic background. Thus, many of the historic ore discoveries began with recognizing some interesting "float" of ore-bearing boulders (an anomaly) and then kicking the moss off a likely looking area. If the prospector liked the looks of the new exposure, he kept testing his geologic assumptions by digging holes, sinking shafts, and driving tunnels until he made a significant discovery or until he ran out of money and patience.

Mineral seekers operate in much the same manner now, except that the cover has become thicker and the indications more delicate. If the target deposit is concealed by pre-ore rock and residual soil, advantage is taken of any worthwhile available evidence. There may be favorable structure leading to depth, a leached and decomposed outcrop of acceptable character, or a geophysical and geochemical anomaly that can be recognized as a part of the affected zone which surrounds some orebodies.

If a valuable mineral deposit is suspected to lie beneath post-ore cover, all of the evidence from the nearest outcrop, the district, and even from the region, is projected into the most favorable target area. The job of ore-finding then hinges upon the use of geophysical data and groundwater geochemistry, aided by such evidence as can be gained from deep-rooted plants and from drill holes. Geologic projection had a prime place in exploring for deep placer leads beneath volcanics in Australia in the last century, and geologic projection has acquired an even greater place in projecting conditions for geophysical targets beneath pediment gravels in the Southwestern United States within the past 20 years. There are also other ways in which a particular mineral deposit may have become concealed as shown in Figure 9. Examples of such deposits discovered, many of them since 1947, are given in Table 4.

The "blind" orebody, best typified by deep discoveries in the Coeur d'Alene district, Idaho, has provided a first-rate challenge for structural projection from existing mine workings. This type of work, utilizing the geologist's entire bag of tricks, every geochemical and laboratory-supported mineralogical guide, and every geophysical technique that can be carried underground, has been responsible for the longevity of both the Magma Mine at

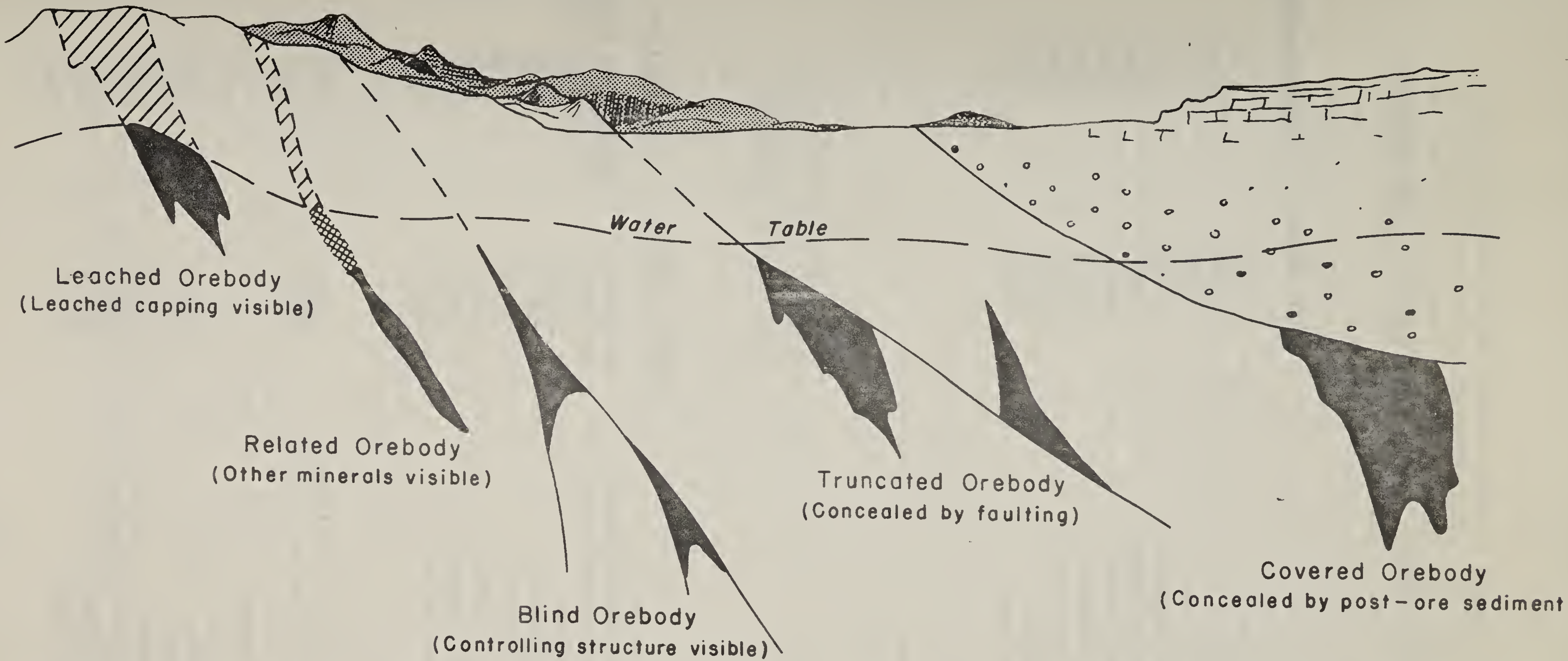


Fig. 9 - Idealized representation of various types of concealed orebodies. With surface outcrops of valuable minerals long since discovered and worked, techniques for recognizing indications of hidden mineral deposits are now of vital importance in the search for minerals.

Table 4

DISCOVERY EXAMPLES: CONCEALED EXPLORATION TARGETS

A. Leached Outcrops:

Orebody Name	Depth to Ore	Recognition Date
Bingham, Utah (Copper)	25 ft.	1904
Ely, Nevada (Copper)	100 ft.	1904
Ajo, Arizona (Copper)	50 ft.	1911
Inspiration, Arizona (Copper)	400 ft.	1915
Copper Cities, Arizona (Copper)	20 ft.	1942
San Manuel, Arizona (Copper)	150 ft.	1945
Happy Jack, Utah (Uranium)	200 ft.	1947
Silver Bell, Arizona (Copper)	100 ft.	1948
Safford, Arizona (Copper)	400 ft.	1956
Esperanza, Arizona (Copper)	95 ft.	1957

B. "Zoned" Orebodies:

District or Mine Name	
Butte, Montana	Ores of several metals found at various depths throughout history of mine and district.
Rico, Colorado	
San Juan, Colorado	
Iron King, Arizona	

C. "Blind" Orebodies:

Orebody Name	Depth to Ore	Discovery Date
Coeur d'Alene deep orebodies, Idaho	to 4300 ft.	various since 1880's
Big Indiana Orebodies, Utah (Uranium)	70-2500 ft.	various since 1940's
Viburnum, Missouri (Lead)	1200 ft.	1955
Faith, New Mexico (Uranium)	400 ft.	1955
Hogan, New Mexico (Uranium)	350 ft.	1958
Burgin, Utah (Lead-Zinc-Silver)	1000 ft.	1958
Copper Basin, Nevada (Copper)	200 ft.	1961
Copper Creek, Arizona (Copper)	2000 ft.	1966

D. Truncated Orebodies:

United Verde Extension, Arizona (Copper)	1500 ft.	1914
Kalamazoo, Arizona (Copper)	2500 ft.	1965

E. Beneath Post-Ore Sediments:

Pima, Arizona (Copper)	225 ft.	1951
Daisy, Arizona (Copper)	337 ft.	1953
Mission, Arizona (Copper)	200 ft.	1954
Ambrosia Lake, New Mexico (Uranium)	340 ft.	1955
Palo Verde, Arizona (Copper)	365 ft.	1956
Twin Buttes, Arizona (Copper)	400 ft.	1964

Sources of data: various

Superior, Arizona, and the Copper Queen, at Bisbee. With such geologic work, the book is never really closed on an old mining district. Figure 10 illustrates the great vertical range of ore shoots in the Coeur d'Alene district and gives an idea of the depth at which some have been found.

The leached type of deposit illustrated in Figure 9 has been the focus for repeated investigation in districts where a few shallow mines and pits once provided small tonnages of oxidized ore. Techniques of leached outcrop evaluation are of longstanding importance and are still prime subjects for research. The uranium mines in the Blind River area of Ontario and several new porphyry copper mines in the Southwestern United States owe their existence to a thorough analysis of the exposed and leached guides to ore. Geophysics, especially new electrical methods, have come to play a major role in assessing the characteristics of orebodies hidden beneath the zone of oxidation.

The zoned orebody concept is of particular significance in examining old and even newly-forgotten mining camps where the ore "played out" at depth or underwent changes of mineralogical nature. Shallow-seated silver ores at Kutna Hora, Czechoslovakia, were mined from the 13th to the 17th Centuries and were essentially exhausted, but the present day Turkanksa Mine, several kilometers to the north and in deeper ground, is producing zinc ore from extensions of different characteristics in the same veins. The effect of depth zoning is especially well-illustrated in a sulfide orebody that has been discovered beneath a barite deposit at Walton, Nova Scotia. The illustration is particularly interesting in that the discovery of the barite-sulfide complex began with an examination of an isolated and unimpressive outcrop of only a few square feet in area. There are, no doubt, many more discoveries to be made among innumerable so-called "teaser" districts, providing that the time can be taken to allow for a high degree of geologic thought, well-placed geophysical investigations, and thorough studies of the older mine workings. Inasmuch as the actual processes which result in the zonal distribution of minerals are still not well understood, there are undoubtedly more disappointments than successes yet to be encountered.

The search for truncated orebodies is as old as mining itself. The challenge is especially attractive inasmuch as it is comparable to the big fish that got away, and there is a great deal of potentially valuable evidence available at the exposed fault surface. The Kalamazoo orebody discovery at a depth of 2500 feet on the San Manuel Fault in Arizona is a prime example of a modern and successful ore finding effort utilizing all available geophysical and geochemical techniques to supplement good structural geologic analysis.

Concealment by post-ore cover, such as by volcanics and consolidated or unconsolidated sediments, makes the setting for some of the most fascinating modern case histories in ore discovery. It is here that geophysics has played its greatest role to date. The depth of mineral deposit discovery by drill hole has been commonly less than 100 feet, as at Kidd Creek and Mattagami in Canada where much of the surface is mantled by glacial deposits. Less often, but with increasing frequency, there have been direct discoveries of orebodies beneath post-ore cover at depths of 100 feet (Maramora, Ontario), 200 feet (Pima, Arizona), 400 feet (Twin Buttes, Arizona), and 1,200 feet (Viburnum, Missouri). The potential for still deeper direct discoveries beneath post-ore cover with the full utilization of geophysics is fascinating and real. Deep penetration geophysics encompasses some very difficult problems in energy, resolution, and interpretation. These problems are under constant research investigation.

Modern case histories of ore-finding beneath post-ore cover have a particularly noteworthy feature. In a majority of cases, there has been a geologic *anchor point* in a few nearby outcrops, in district trends, in abandoned prospect shafts, and in older drill hole information. At Mattagami, Ontario, the geophysical surveys which led directly to the ore discoveries were well-placed within a favorable mineral belt, and the surveys were well-interpreted on the basis of existing geologic information from a few small and widely spaced outcrops containing minor mineralization. The Pima orebody discovery in Arizona, a real milestone in geophysical exploration, was made in a well-known mining district which had been carefully selected by the geophysicists from a list of possible target areas. The

Mission orebody discovery in Arizona was made by using a combination of geophysics plus district trends plus a study of mineralogical features in small outcrops.

The geologic anchor point associated with a geochemical or geophysical investigation has provided the favorable indication upon which the reconnaissance pattern has been based, and it has provided a basis for identifying anomalies, background charactersitics, and threshold values. Geologic, geophysical, and geochemical investigations have been most effective in the search for concealed ore deposits when they were permitted to develop side-by-side. A sampling traverse or a line of instrument stations has been most valuable when it is locked onto a well-studied outcrop or a mine working. A geophysical interpretation has been most accurate when supported by a drill hole, preferably at an early stage in the investigation so that more geophysical work could follow.

Inasmuch as geophysical and geochemical work has been reported in hard figures, while geologic work has been less definite, there has often been a rush to decision without allowing for the time-consuming geologic study needed for a complete exploration effort. This is like using a "go or no-go" gauge. The reason has most commonly been tied up in the economics of exploration situations. Lengthy preliminary studies are expensive, there has usually been an exploration lease with a "time is of the essence" clause, and decisions have to be made. These conditions may well have caused many an exploration program to go off half-cocked without taking time to develop the all-important geologic anchor point. Under such conditions, both the geophysicists and the drillers have operated with only a portion of the information which they should have had.

The aspect of more deep exploration projects with emphasis on orebodies beneath post-mineral cover makes the position of a continuous geologic staff with regional know-how more important than ever. As minerals seekers reach for deeper and more obscure targets, it has become less in the interest of good economy to turn an exploration department or a national exploration policy on and off as a result of changes in the demand for a particular mineral commodity. A well-oriented and capable exploration organization of a size which can be maintained through a long period of time could provide at least the first step to needed geologic anchor points on short notice. The anchor point is likely to be based upon regional study and thorough familiarity with a particular area. It seems poor economy to launch an exploration program for a concealed orebody without a preliminary investment in the information needed to select the proper geophysical techniques, the most effective geochemical sampling patterns, and the best drilling sites. Such informational continuity has become increasingly critical in the past two decades.

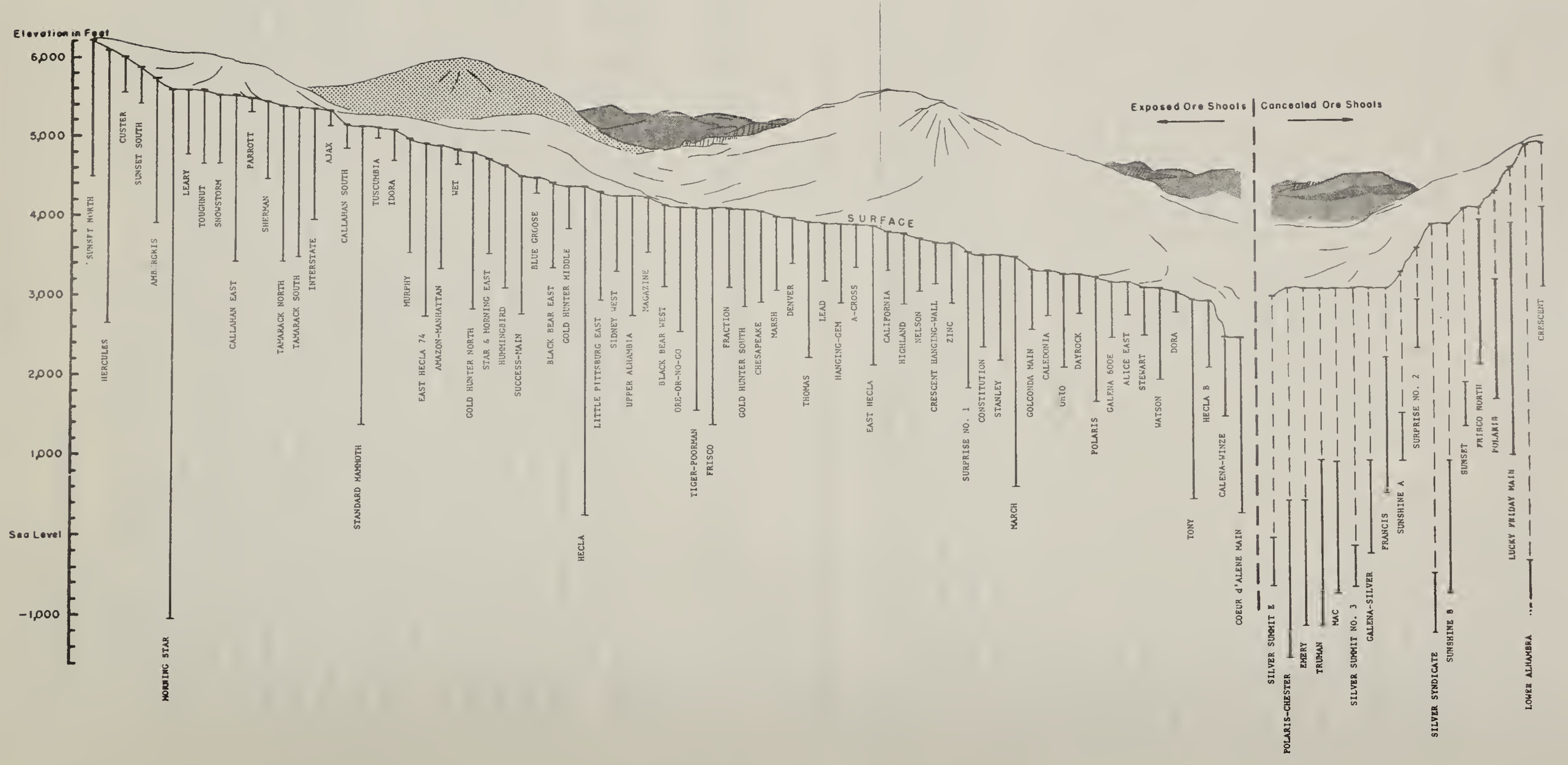


Fig. 10- Exposed and concealed ore shoots in the Coeur d'Alene district of Northern Idaho. Although many such districts were originally discovered by the finding of surface outcrops of metal-bearing minerals, their lives have been prolonged only because active exploration has discovered previously concealed orebodies at depth.

E. CURRENT EXPLORATION PRACTICE

1. Regional Reconnaissance

Present minerals exploration in the United States in some respects is similar to exploration as it was conducted prior to 1872. In other ways it reflects the numerous technical and economic changes that have taken place since that time.

In the regional reconnaissance stage of mineral exploration, most or all of the preparatory work is now done as an office study. Mineral commodities are selected for exploration, and a study is made of the environments in which these commodities are likely to occur. This involves a review of the geologic literature, evaluation of the types and abundance of areas of known mineralization, and the potentials of different environments to contain deposits of the type desired. Areas within selected environments believed to be favorable are then subjected to actual field reconnaissance.

Theoretical geologic studies are often made by projecting known structural and formational trends to determine favorable geologic conditions not previously recognized in the literature. Aerial photographs and topographic maps are used quite often as a base on which to plot information, and photogeologic maps are frequently constructed by plotting features noted on the photographs for areas which have not previously been mapped. Brief trips to areas of interest may be made for familiarization.

The importance of this preparatory work has gained considerable recognition within the last two decades. As one prominent (and successful) consulting geologist stated, even before 1947,

> "Most recent discoveries of ore by geologic methods resulted from detailed studies of structural conditions and these had detailed large-scale mapping as their base."[34]

Another authority restated this after the close of World War II:

> "In these days most projects for the exploration and development of metals are carried out under some form of geological guidance, whether it is supplied by professional geologists or by engineers who have themselves acquired a knowledge of geology, and whether it is based on original investigation or on surveys by government or scientific organizations."[35]

If the office study suggests favorable target areas, these areas are then examined in the field, first perhaps by airborne visual reconnaissance and geophysical surveys, followed, if the area still looks favorable, by reconnaissance geologic mapping, plus ground geophysical and geochemical surveys. The general land availability for acquisition is checked, and submittals by property holders already in the area may be examined.

At this stage geochemical surveys are designed to detect suitable target areas as rapidly as possible and to provide background data. Samples are spaced far apart, sometimes a mile or more, usually along major tributaries of streams that drain large areas. Once detection of an anomaly is made, its extent is outlined by further geochemical sampling. Surface samples are then collected over the specific target area at intervals of 500 feet apart, or less.

Widely-spaced geophysical surveys may also be conducted. Airborne geophysics is often used during this phase of exploration as it can permit coverage of large areas in a relatively short period of time. Following discovery of an airborne geophysical anomaly, ground geophysical surveys are made, normally with geological reconnaissance mapping of the pertinent area.

The combination of geologic information, theory, and/or geochemical and geophysical work is designed either to eliminate the area from further evaluation or outline one or more smaller target areas within the overall reconnaissance area. If collection and evaluation of the data have delineated a target area of potential mineral-bearing ground, work proceeds to the next phase.

2. Target Area Examination

Once a target area is selected and its land status is determined, the ground is either staked, optioned, or leased, or a prospector's permit is secured, depending upon the ownership status of the minerals in the area. If the ground is to be staked (i.e., if its minerals are in the public domain and legally locatable), the necessary supplies are secured (wooden posts for monuments and containers for the claim notices) and location monuments are emplaced on the ground itself. Generally the distance between location monuments is paced or measured roughly with a tape in order to cover the ground as quickly as possible. This is done to forestall acquisition by competitive interests. Ten claims can often be staked this way in the same amount of time required to survey accurately two or three claims.

Once the location monuments are in and the notices recorded, the corner and end monuments are put in. Although the maximum legal size of claim is normally staked, experienced exploration crews usually stake their claims so that there is from 10 to 50 feet of overlap of one claim onto the other. This is done to avoid leaving fractions which can be claimed by adverse parties.

If the terrain is very rough or vision is obscured by vegetation, the initial paced or tape traverses may not be considered sufficiently accurate and the monuments are surveyed to ensure complete coverage of the ground. Adjustments in the claim corner locations are made as necessary and an amended claim notice is filed. If the pace or tape measurements are considered to be reasonably accurate with no danger of fractions, formal surveying may be left to a later date.

More often than not the ground which is staked contains pre-existing claims. The new claims are staked to overlap the older ones, leaving no fractions. The owner of the older claims is usually contacted and his claims are leased, with option to purchase.

In most areas, validation of the claims requires that location work be performed within about 90 days of claim location. This work consists of digging (or blasting) a "discovery pit," a hole at least eight to ten feet deep, depending on the type of excavation. In some states an exploratory drill hole of a specified depth may replace the "discovery" pit. The drill hole is generally preferred, both by the surface owner and the mineral seeker, as several claims (at least in Arizona) can thus be validated by one drill hole and the ground is not unnecessarily torn up by numerous pits or bulldozer trenches. Furthermore, under current conditions, the drill hole is much more likely to provide useful information than is a relatively shallow "discovery" pit.

The purpose of the drill hole or pit at this stage is to meet the legal requirements for a discovery of mineral in place. In practice, however, alluvial fill may be too thick over part or all of the potentially mineral-bearing rock, so that penetration of the ground is limited to the depths and expense required by the various state laws. Exploration groups prefer to make their major drilling expenditures on the best-looking portions of the target area. If these are favorable, drilling will later extend outward to prove or disprove ore mineralization on the surrounding claims.

The custom among most exploration men has been generally to respect the rights of the owner of a group of claims so long as they are actively being explored and maintained, whether mineral in place is shown or not for each and every claim. This is because those in the industry are well aware that the cost of legally "proving up" each individual claim may prematurely divert an excessive amount of funds available, leaving an inadequate amount to examine the principal specific target or targets within the target area. Determination of these targets often requires several months' study longer than the period legally allowed for location work. If the ground is not staked until a specific target is determined, work in the area may attract conflicting interests who will stake the ground for their own advantage.

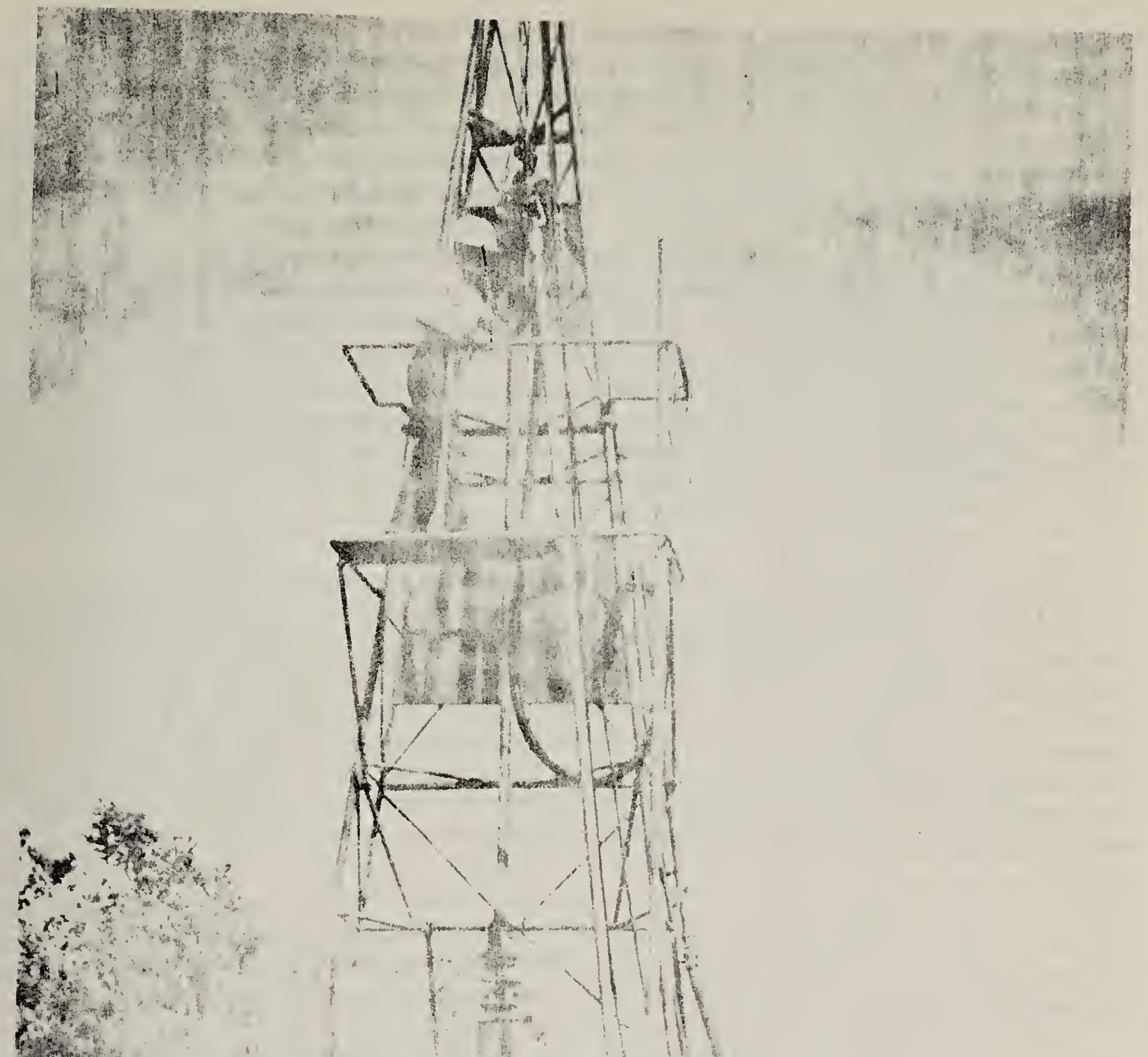


Fig. 11 · Diamond drilling to evaluate a potential uranium orebody in Northern New Mexico. The use of larger and more technically sophisticated equipment in exploration has substantially increased both capabilities and costs. (Photo courtesy of Thomas Nye)

Security, therefore, demands that the general area of interest be staked in advance of the detailed exploration work necessary to determine and test the specific target.

The exact location of a valuable mineral deposit, of course, is not known in advance of exploration. Rather, an area containing, or suspected to contain, favorable evidence of mineral deposition is selected and acquired. If there were some way to determine the precise location of an orebody in advance, the number of claims or ground area taken up in the initial phase of the exploration process could be substantially reduced for most commodities. Unfortunately this is not the case and probably never will be. To the contrary, it is common, particularly in the search for metals, that what is at first believed to be the principal target is later disproven by detailed drilling. This same drilling, however, may provide evidence of favorable mineralization elsewhere. This mineralization is then tracked by subsequent drilling until either an orebody is found or circumstances cause abandonment of the project. The actual mineral deposit may be shifted somewhat from the original site of the principal target, or it may be completely separate from it. Prudence demands, therefore, that sufficient ground be taken up initially to ensure that the entire potential area of mineral deposition is covered.

Once a study has been made of a region and a specific target area selected for examination, additional, more detailed geologic mapping and/or geochemical and geophysical work is usually required. Depending on the type of mineral commodity and the complexity of the local geology, all or none of these techniques may be used. Ordinarily, at least some further study of the area is made before the specific target is selected, even though it may be restricted to a review of previously acquired data. As a rule, metallic mineral deposits are smaller and situated in a more complex geologic environment than non-metallic mineral deposits, thus requiring more intensive and detailed geologic study.

At this stage of the exploration process, geologic mapping is done on a scale of from 50 to 500 feet to the inch, augmenting data recorded on scales of 500 to 5000 feet to the inch during the reconnaissance phase. Geochemical samples may be collected at intervals of 50 to 200 feet apart on a grid pattern covering the area, and closely-spaced geophysical traverses may be made over part or all of the area. These traverses may be 100 to 1000 feet apart. Rock samples are frequently collected for microscopic and/or x-ray analysis of the mineralogy as it relates, or may relate, to ore deposition.

The collected data are analyzed, and one or more specific targets are selected for drilling. Normally, where larger firms are involved, bids are requested from contractors for road construction, drill site preparation, and the actual drilling. Funds are allocated, contracts drawn up, and the project proceeds to the next phase.

The decision as to what constitutes a target area, and what is a specific target deposit within that area, depends partly on the available data and partly on the interpretation of those data. Interpretation, of course, varies with the experience and skill of the individual(s) making the interpretation. Target selection also depends on the amount of risk that is to be assumed and the funds available for exploration. Only rarely are all the data and their interpretation entirely favorable. Such data include the presence and relative abundance of ore minerals and/or minerals normally associated with ore, favorable conditions of rock associations and structures (faults, fractures, veins, and attitudes of the rock formations), and geochemical and/or geophysical anomalies. Normally, the data are incomplete and open to several interpretations. The evidence available is weighed against the cost of testing one or more interpretations and the potential value of the mineral deposit sought.

One of the most critical factors involved in exploration decisions is the size of the potential ore-bearing area. If it is too small the target must be dropped, but what is "too small" depends on who is doing the exploration. A small high-grade deposit of limited tonnage may be perfect for a small mine or company but of little interest to a large company, whose overhead and investment in manpower and capital facilities is much greater.

The amenability of a potential orebody to profitable mining or metallurgical techniques is also a factor in target selection. A waste-to-ore stripping ratio which is too high and costly may eliminate a particular mineral deposit, otherwise of good quality, as a target. A prospect containing silver-bearing rock with a high manganese oxide content may be eliminated from consideration, as silver is difficult to separate from the manganese oxide in many instances. Deposit accessibility and the climatic conditions under which mining would have to be done also affect target selection. The potential orebody to be explored must have a higher anticipated value if it is more distant from transportation, power, and marketing facilities than other, more accessible targets.

Because of differences in interpretation and changing technology and economics, a mineralized area or an area of potential mineralization may be considered or explored by a number of individuals and companies before a useable mineral deposit is found. This has been the rule rather than the exception for most mines in operation today. As a result, mineralized areas and districts now inactive but having had previous production, no matter how brief or small, are now being reevaluated and explored more than ever before by individuals and companies of all sizes. Rejection of a particular property, district, or mineralized area by one or more companies, therefore, is not conclusive evidence of its lack of potential.

A minerals exploration group has as its objective the testing of a target or target area with the minimum expenditure of funds necessary to prove or disprove the interpretation of already available data or theory. Only rarely are there sufficient reasons and funds available to completely invalidate a target area for further consideration. A given company may have twenty exploration projects and a one million dollar exploration budget for a given year. This would allow an equal expenditure of $50,000 per project, or about two to five drill holes of moderate depth plus geologic and assay work. If an interpretation and specific target selection are wrong, an orebody can easily be missed. The odds for success for a particular firm may often be greater if twenty targets are tested with a few holes on each than if all of the available funds are expended to prove or disprove one target. As several authorities have noted,

> "Although theories of genesis and of ore occurrence provide the background for all geological thinking, they are not infallible guides, for it is unlikely that even the best theory is correct in all of its details. After all, it has to be based on circumstantial evidence. Since none of us were on hand when an ore deposit was formed, we can never know exactly what the conditions were. We have to base our conclusions on inferences from the facts that we have and we never quite have all of the facts. Some of the details must always be in doubt and we must never overlook the element of doubt. In short a theory must never be taken too seriously.
>
> "Above all, a prediction that ore will not be found in a given place should be made only on the most conclusive evidence. As McLaughlin and Sales put it [McLaughlin, D. H., and Sales, Reno H., Utilization of geology by mining companies; in *Ore Deposits of the Western States*, A.I.M.E., Lindgren Volume, p. 689, 1933], 'Negative theories . . . in general, are far more dangerous than positive ones. Loss from unsuccessful attempts to find ore will rarely exceed the cost of development to test the ground (plus possible initial payments on options if a new property is being investigated), but negative ideas blindly followed might lead to the unforgivable sin of missing a great opportunity to find or acquire an important orebody.' "[36]

Once a specific target area has been chosen for detailed examination, access roads and drill sites are prepared, following which drill rigs are moved in. Initially, from one to five holes are ordinarily drilled. If results are favorable, additional drilling is done. If the results are unfavorable, the project is usually dropped. The results of this initial drilling phase are generally the most crucial, and with few exceptions (e.g., large continuous and uniform beds

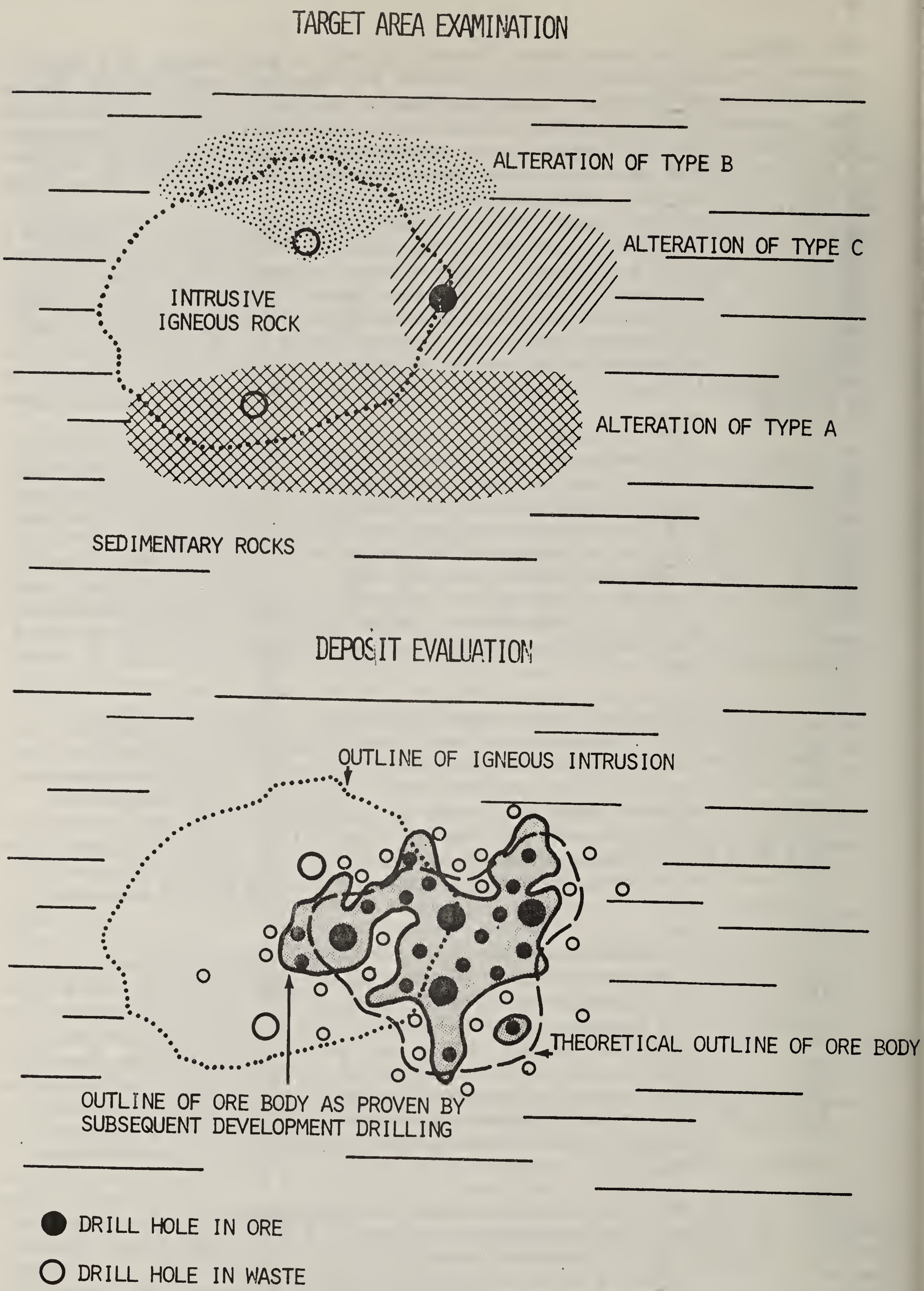


Fig. 12 - Geologic information increases and changes the apparent geologic situation as the exploration of a particular deposit progresses. The picture in the initial stages may differ markedly from the actual circumstances.

of non-metallic mineral deposits which are gently-dipping or flat-lying), the data are not sufficient to make a definite decision as to the presence or absence of an orebody.

The initial results are then weighed in terms of risk remaining and the funds available. The expenditure must not be disproportionate to the size of the mineral deposit anticipated. Otherwise, there would be little room for profit once an orebody were found and mined. Hence the decision continues to be a matter of judging the odds for success in the light of the new data acquired.

3. Deposit Evaluation

Initial exploration drilling tests likely sites for the occurrence of ore minerals. Once a discovery of ore minerals is made, the rough extent of ore-grade mineralization is outlined with a widely-spaced drill pattern. In the third phase, delimiting of the orebody is done with closely-spaced holes. It is in this third phase that continuity of ore-grade mineralization (or lack of it) is determined. At this point the shape of the mineral deposit is generally modified from the outline inferred from previous drilling. Not infrequently, sufficient areas of waste are discovered between the earlier drill holes to raise serious doubts as to the economic worth of the deposit or to disprove its value.

More often than not, the initial phase of exploration drilling consists of tracking the evidence of mineralization in hopes that it will lead to ore. So long as the results are encouraging, the tracking will continue. Sometimes a "teaser" of mineralization is encountered, and the decision to continue or not is a difficult one. If the exploration manager terminates the project too early he may have missed an orebody. Conversely, continued drilling of such an area where no ore is to be found will cost excessive sums of money, time, and manpower.

Even drilling has its limitations as an exploration tool. A diamond drill core provides a cylinder of rock from about one to two inches in diameter. Other types of drilling yield cuttings from a hole which may vary from six to 12 inches in diameter. In relation to the volume of rock involved, these are relatively small samples. Furthermore, there may be no guarantee of the continuity of mineralization shown in adjacent drill holes. The amount of continuity likely varies with the type of ore deposit. In some veins, ore shoots are very spotty; in others, they may be continuous. There is a better chance of continuity in base metal veins than in precious metal deposits, and in precious metal veins, there is a better chance with silver than with gold.

With diamond drilling costs at $10 per foot or more, there is a practical limit to the closeness of spacing of the drill holes. In vein deposits, even where drilling results are favorable, considerable risk is usually entailed and the development of underground workings is necessary for full evaluation. (See Chapter 5, Figures 64 and 65.) Partly in compensation, the capital investment required to bring vein deposits into production is usually far less than with the large disseminated deposits, such as the porphyry coppers. With the porphyry coppers and similar types of deposits, such as Climax molybdenum and Carlin gold, the ore minerals are distributed through the host rock with surprising uniformity, like very small raisins in a very large pudding. (See Chapter 5, Figures 71 and 72.) This means that exploration drilling, even with a rather wide spacing of holes, can approximate very closely the size and shape of the orebody, and its average metal content. All American porphyry copper deposits have been blocked out in this way, with limited underground workings driven to check the drill sampling, often in conjunction with the acquisition of bulk samples for a pilot mill. Nevertheless, at some porphyry copper deposits designed to be mined by open pit methods, the stripping of waste overburden has occasionally been started on the basis of drilling alone.

The stripping of waste overburden, or the driving of underground extraction openings is properly called mine development, not mineral exploration. Nevertheless, exploration, even at open pit mines, continues throughout the life of the mine. In vein mines, new orebodies must be found to replace those mined out, and it is seldom possible to find all of these during the strictly exploration phases. In large disseminated deposits, in spite of the relatively even distribution of ore minerals, the distribution does vary locally, and the variation may not be disclosed by the drilling. Faults and other critical structures also may not have been disclosed initially but only upon actual excavation.

Most exploration projects carried out by large companies are under the control of a project manager, who answers to the district geologist or to the firm's home office. Under the project manager are one or more geologists and samplers who keep a record of the drill core or cuttings, collect samples, have them assayed, and record the necessary data. The logging of core or cuttings consists of recording the amount of material recovered for the lengths of hole drilled and the location and type of rock, structures, attitudes of rock formations, location and abundance of fractures, faults, and veins, rock alteration, and ore and gangue minerals cut in each drill hole. Written and graphic representations of the data are prepared and projected between holes to gain a picture of the subsurface geology and the distribution of minerals associated with ore.

Core or cuttings suspected to have values are split, one-half being retained for further examination if necessary and one-half being sent to the assayer. Assays are plotted on the drill records. If ore is encountered, reserve and grade estimates are calculated and plotted on maps and sections through the drill holes. These estimates are revised as new data are received.

In some types of mineral exploration (e.g., for evaporites and uranium), probe instruments are lowered down the holes after they are drilled and a record of electrical and/or radiometric response of the various formations encountered in the holes is made. These data augment information about the types of formations and evidence of mineralization previously obtained from core or cuttings.

The evaluation of data is a continuing process applied to every step of the exploration process. Work continues so long as the risk of failure is progressively reduced. Once the existence of a mineral deposit of current or potential value is demonstrated, the project is normally turned over to the mining personnel. These conduct bulk sampling (through shaft sinking or other excavations), metallurgical testing, and feasibility studies of various mining methods. These people make the mine. They decide when, how, and sometimes if, the deposit should and/or can be mined.

Some mineral deposits may not meet the requirements of an orebody for a particular firm after a thorough evaluation is made, and the property is then either reluctantly dropped or sold to another company, if it fits that company's criteria. The common parameters, which vary from company to company are size, anticipated mine life, and rate of return on investment. The Battle Mountain (Nevada) and Sierrita (Arizona) disseminated copper deposits were discovered and subsequently examined by the American Smelting and Refining Company and Bear Creek Mining Company, respectively. The managements of those companies, however, relinquished their interests in the properties as unsuitable for mining. The Duval Corporation acquired both properties and, after further exploration, development, and evaluation, considered them as suitable for mining.

4. Exploration Entities

Figures 13 through 17 illustrate the general organization of the exploration group and its position in a mining company today. This organization varies in detail from company to company depending on the size and objectives of the company and internal organizational requirements. The exploration group may have its own research, geophysical, geochemical, and land departments or it may depend partly to completely on independent service organizations for these functions. These supporting departments may be organized at the district level in some companies, while in others they are under home office control, being dispatched to individual districts and projects as needed.

The demands of exploration have become so heavy that most new geologists now start their careers in actual exploration with little or no prior practical experience at operating

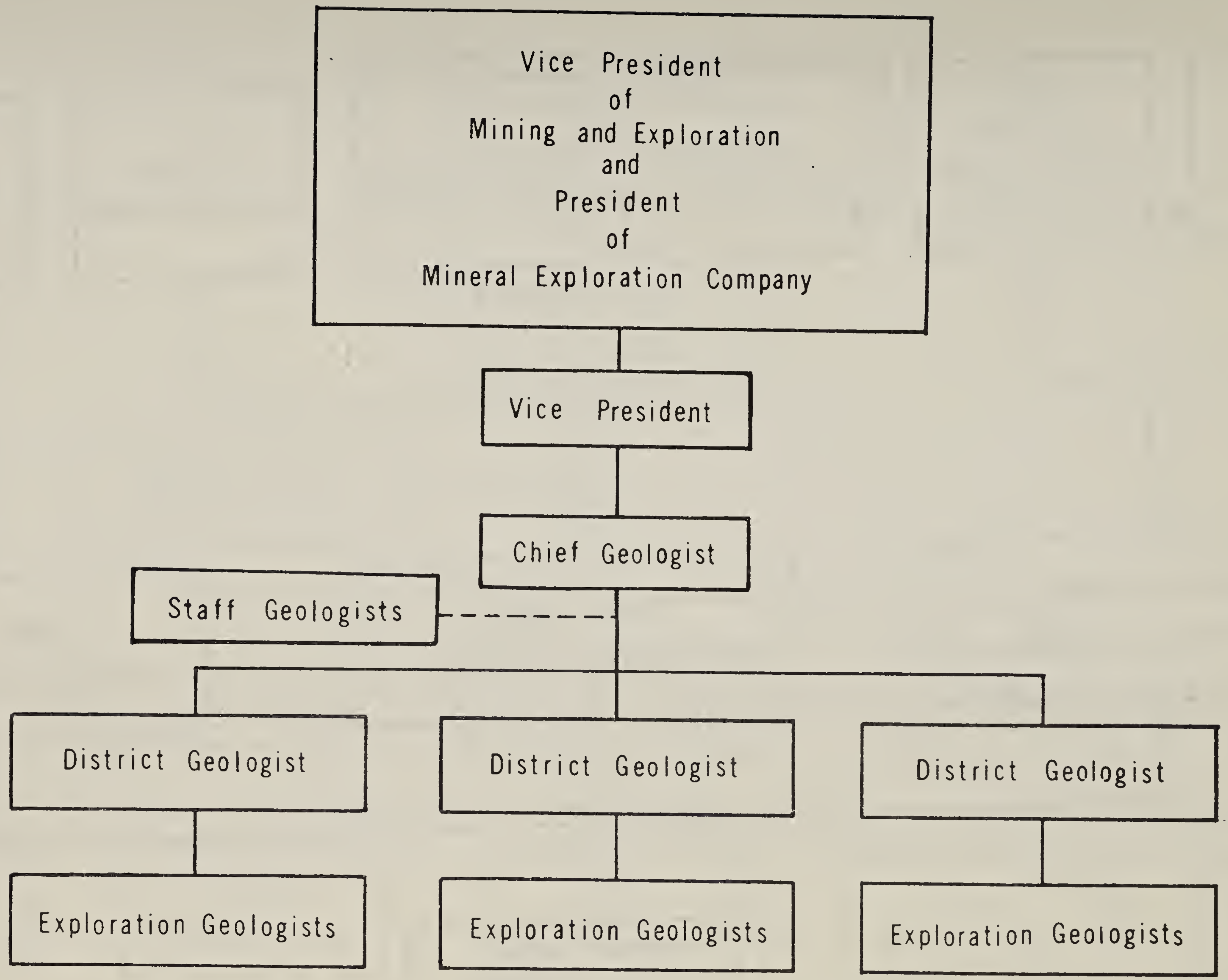


Fig. 13 - Typical exploration organization in a minerals-producing firm.

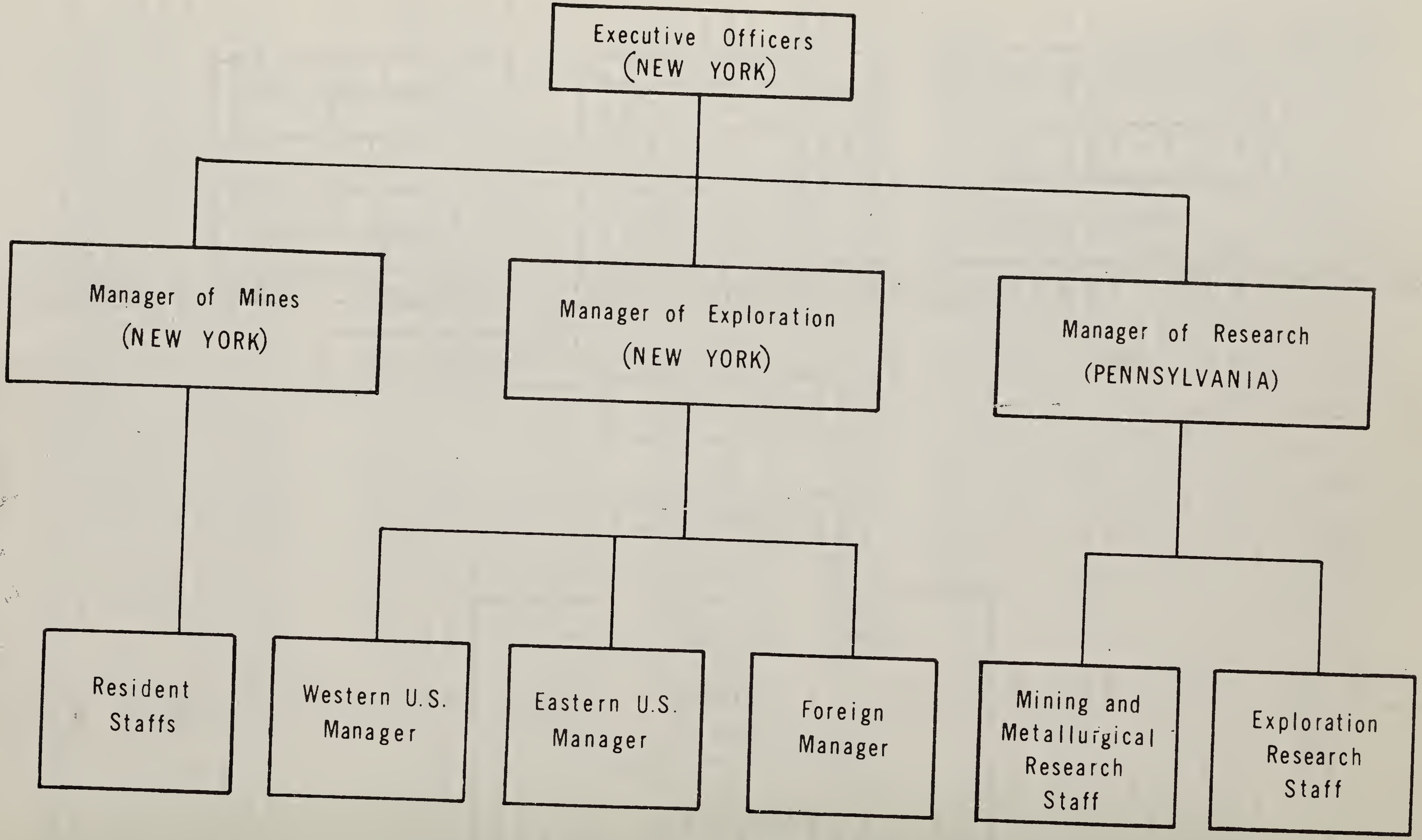


Fig. 14 - Exploration organization of a large non-ferrous metals

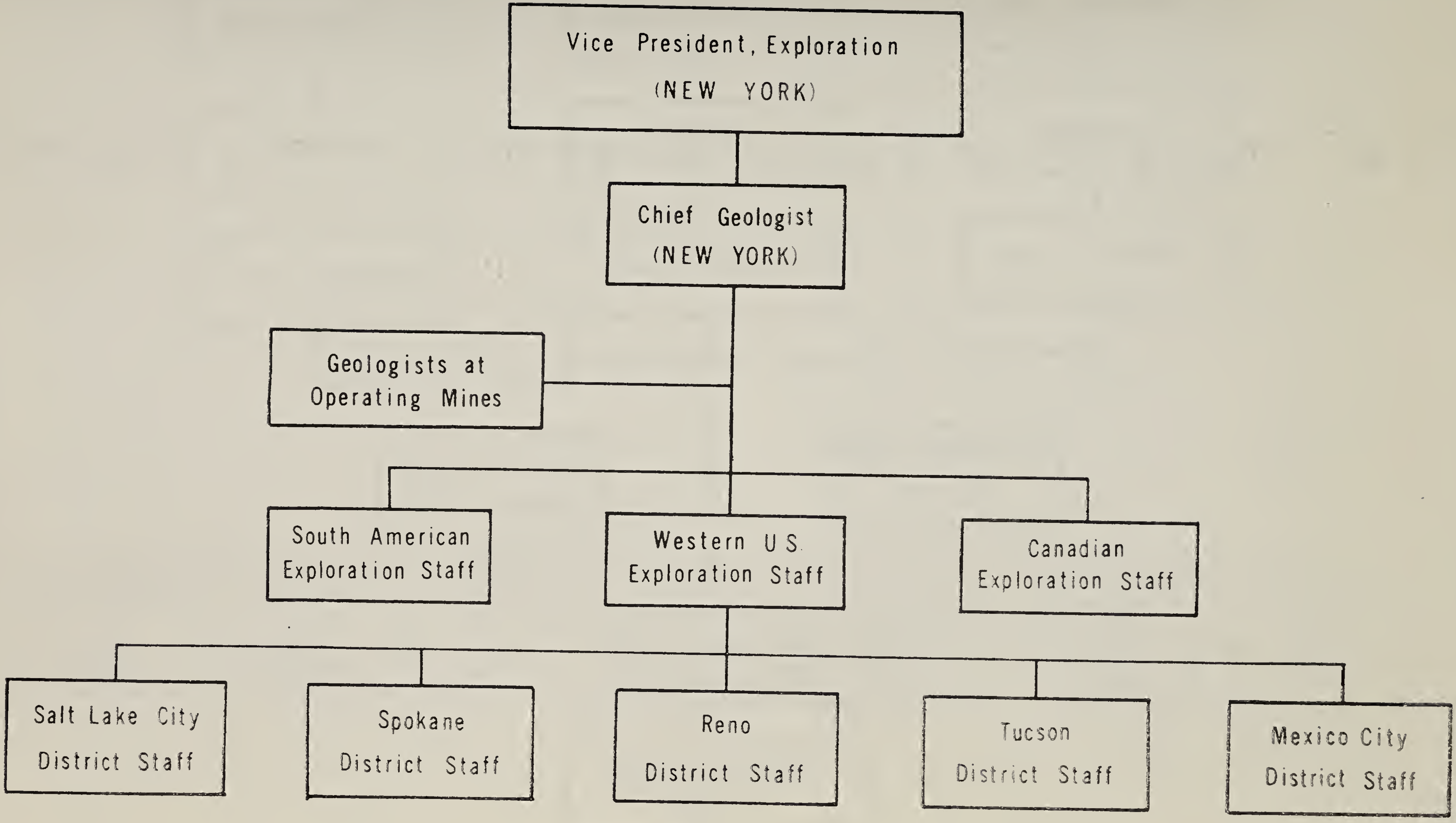

Vice President, Exploration
(NEW YORK)
Chief Geologist
(NEW YORK)
Geologists at Operating Mines
South American Exploration Staff
Western U.S. Exploration Staff
Canadian Exploration Staff
Salt Lake City District Staff
Spokane District Staff
Reno District Staff
Tucson District Staff
Mexico City District Staff

Fig. 15 - Exploration organization of a large non-ferrous metals producer combining both domestic and foreign exploration activities.

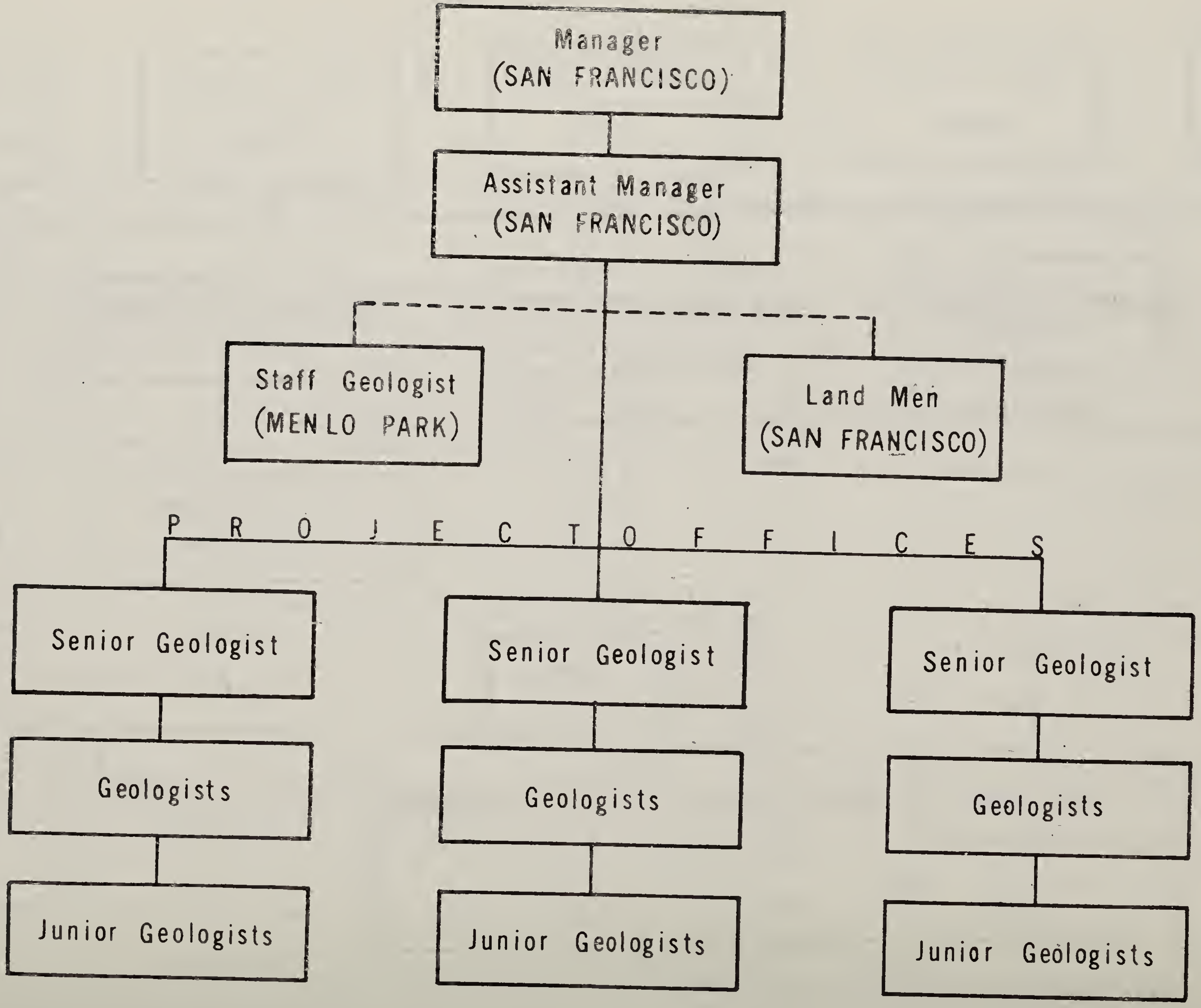


Fig. 16 - Exploration organization of a major non-ferrous

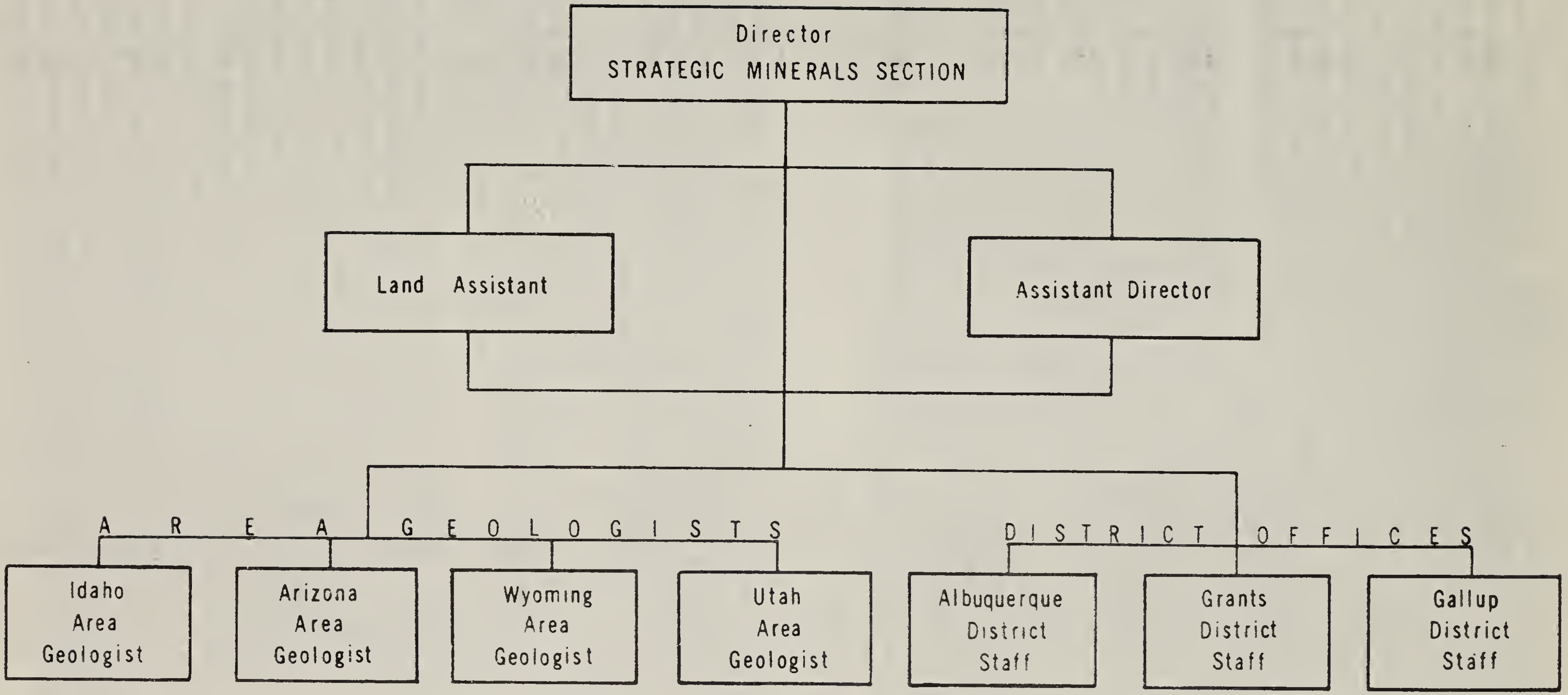


Fig. 17 - Exploration organization of a major minerals producer seeking both non-metallic and metallic mineral deposits.

mines. Present land men are often geologists or engineers who have had experience in exploration and mining, enabling them to spot and solve technical problems related to land acquisition more readily than the person without a technical background. Often the land man must advise the company's legal staff on what steps to take, as he is more familiar with the technical and economic consequences of various acquisition terms and land laws than the lawyers, to whom mining law is but a part of their duties to the company.

In some organizations, land men and geophysical and geochemical exploration teams have been assigned to district or regional offices, and work under the direction of the district geologist. Other companies have these supporting personnel in separate units operating out of the main office, either independently on specific exploration problems or on call to the district offices as needed.

Exploration policy is usually dictated by the home office and, for any one organization, may be largely restricted to one or two commodities or include any mineral commodity which can be profitably mined, depending upon the individual company's needs and outlook. Some companies have stringent restrictions on the minimum size and grade of orebodies which they are willing to mine. Bear Creek Mining Company, for example, found and examined the Sierrita disseminated copper deposit south of Tucson, Arizona, but Kennecott, the parent company, decided the deposit was too small and low-grade, and interest in the property was relinquished. The Duval Corporation acquired the property within a year after Bear Creek dropped it, and is now preparing it for production.

Some district exploration offices operate on specific budgets which are submitted to the home office in advance for revision and approval. Others are either assigned specific budgets or are given basic operating funds which are supplemented by additional funds as required for individual exploration projects as they arise.

5. Exploration Costs

Local exploration office costs (excluding specific project costs on target area examinations and deposit evaluation) include such items as travel, assays, equipment, salaries, office rent, and vehicle maintenance. The costs of a one- or two-man office, plus one secretary, with moderate travel, would range from $40,000 to $75,000 per year. A three-man (each a geologist) office, plus one secretary, with variable use of consultants and part-time help, and moderate to heavy travel, would be between $100,000 and $150,000 per year. A much larger regional office with 15 to 20 men (including geologists, geophysicists, field and technical assistants) plus from six to eight secretaries, a geochemical laboratory and staff, making variable use of consultants and part-time help, and with moderate to heavy travel, would range from $300,000 to $800,000 per year. These costs are approximate, of course, and vary with personnel salary ranges, the amount of field work done, and the equipment purchased and used.

Claim location and validation costs on large blocks of claims (100 to 300 claims or 2,000 to 6,000 acres) commonly staked to cover large low-grade targets deposits normally range from $100 to $200 per claim. Variations in such costs depend on the accessibility and roughness of the terrain, the experience and salaries of the personnel doing the work, and the general ease with which the location work can be done. These figures do not include the cost of formal surveying. Claims are usually staked initially using a compass and pacing, or taping the distances with a 100 to 300 foot tape. Formal surveying would add $25 to $100 to the cost of each claim. The cost per claim of staking and doing location work may be considerably higher for small claim groups than it is for large claim groups due to the old principle of higher volume resulting in lower unit cost. Tables 5 through 9 provide examples of different types of exploration costs in the relatively arid portions of the West. Where weather and vegetation adversely affect exploration activity, costs will be higher.

Total exploration costs for specific projects conducted by major minerals-producing firms are substantial and quite variable. The sample of successful mineral exploration projects completed in the United States in the period from 1947 to 1968 shown in Table 10

Table 5

MINERAL EXPLORATION COSTS
SOUTHWESTERN STATES, 1968
(Exploration Support)

Office Studies

Air Photos - Black and White	
Government Stereo-coverage	$0.10 - $0.40 per sq. mile
Contract Stereo-coverage	
2,000 to 50,000 sq. miles	$2 - $8 per sq. mile
10 to 30 sq. miles	$20 - $40 per sq. mile
one to five sq. miles	$100 - $400 per sq. mile
Air Photos - Color - Add 30% to black and white cost	
Photogeology (add to cost of photos)	
Generalized	$2 - $6 per sq. mile
Detail	$8 - $30 per sq. mile
Photogrammetry (including cost of new flying)	
15 to 25 sq. mile area	
scale, 1:12,000	$100 - $200 per sq. mile
scale, 1:4,800	$200 - $300 per sq. mile
Reproduction	
Black line prints	$0.10 - $0.15 per sq. foot of print
Sepia prints	$0.20 - $0.50 per sq. foot of print
Film prints	$1.00 - $1.50 per sq. foot of print
Enlargements	$2 - $5 per sq. foot of print

Laboratory

Geochemical trace analysis (4 elements)	$3 - $5 per sample
X-Ray diffraction mineralogy	$9 - $27 per sample
X-Ray Fluorescence analysis	$4 - $8 per sample
Semi-quantitative spectrography	$12 - $30 per sample
Assays (including preparation)	
Single element	$2 - $7 per sample
Cu-Pb-Zn	$4 - $7 per sample
Thin section preparation	$2 - $4 per sample
Polished section preparation	$4 - $6 per sample
Thin section petrologic study	$15 - $20 per sample

Source: W.C. Peters, from paper, *The Economics of Mineral Exploration.*

Table 6

MINERAL EXPLORATION COSTS
SOUTHWESTERN STATES, 1968
(Regional Reconnaissance)

Manpower	
Base Salaries	
Junior Geologist	\$700 - \$900 per month
Senior Geologist	\$900 - \$1,500 per month
Overhead and Fringe Benefits	25% - 50% additional
Generalized Planning Cost	\$60 - \$90 per man-day
Field Geology	
Reconnaissance Mapping	(Scale, 1:12,000 and smaller)
Simple Terrain	\$20 - \$40 per sq. mile
Complex Terrain	\$30 - \$80 per sq. mile
Detail Mapping	(Scale, 1:12,000 and Scale, 1:4,800)
Prospect Areas	up to \$10,000 per sq. mile
Mining Districts	up to \$20,000 per sq. mile
Transportation	
4-wheel drive vehicle	\$200 - \$300 per month plus \$0.10 per mile
Pickup truck	\$120 - \$150 per month plus \$0.08 per mile
Small fixed wing aircraft	\$30 - \$60 per hour
Small helicopter	\$90 - \$130 per hour with 3 or 4 hours minimum per day
Field Expenses	
Generalized per man	\$12 - \$15 per day
Camp per man	\$7 - \$10 per day

Source: W.C. Peters, *op. cit.*

Table 7

MINERAL EXPLORATION COSTS
SOUTHWESTERN STATES, 1968
(Target Area Examination)

Geochemistry	
Field sample collection, general	$2 - $5 per sample
Field sample collection	
500-foot intervals, rock or soil	$150 - $300 per sq. mile
Reconnaissance, stream sediment	$20 - $40 per sq. mile
Geophysics (Acquisition and Preliminary Data Interpretations)	
Airborne (Fixed Wing)	
Radiometric	$3 - $10 per line mile
Magnetic	$5 - $20 per line mile
Electromagnetic	$10 - $20 per line mile
EM plus magnetic	$20 - $30 per line mile
Airborne (Helicopter)	
Magnetic	$20 - $30 per line mile
EM plus magnetic	$30 - $50 per line mile
Ground	
Radiometric	$15 - $55 per line mile
Magnetic	
Detail	$40 - $85 per line mile
Road, continuous	$3 - $10 per line mile
Road, reconnaissance station	$5 - $20 per line mile
Off-road, reconnaissance	$10 - $40 per line mile
Gravity	$150 - $300 per line mile
Induced polarization	
Reconnaissance	$150 - $300 per line mile
Detail	$700 - $1000 per line mile
Overall average	$500 per line mile
Electromagnetic	
Reconnaissance	$70 - $150 per line mile
Detail	$300 - $500 per line mile
Self-potential	$50 - $140 per line mile
Shallow seismic	$200 - $500 per line mile
Borehole	
Base charge	$0.06 - $0.10 per foot
I.P. plus S.P. logging	$0.20 - $0.60 per foot

About 25 percent of the geophysical costs represent mobilization, transportation, and field camp expenses.

Source: W.C. Peters, *op. cit.*

Table 8

MINERAL EXPLORATION COSTS SOUTHWESTERN STATES, 1968 (Pre-Evaluation Protection)

	Time	Cost
1. Location monuments and recordation of claims		
4-man crew	10 days	$3,500 (wages, expenses, supervision)
2. Monumenting of claim corners and end centers		
2-man crew	30 days	$2,500 (wages, expenses, supervision)
3. Location work		
By core drilling, 2-rigs, 25-holes	65 days	$30,000 (drilling, supplies, drill sites, and roads)
Total Cost:		$36,000
Cost per claim:		$144

Costs for a 250-claim group staked without formal surveying in Arizona, in moderately rough terrain.

Source: E. Wisser and Associates

Table 9

MINERAL EXPLORATION COSTS
SOUTHWESTERN STATES, 1968
(Deposit Evaluation)

Exploration Drilling

Hammer drill to 1000 feet	$3 - $5 per foot
Rotary non-coring	
to 1000 feet	$2 - $4 per foot
to 3000 feet	$3 - $10 per foot
Diamond coring (NX to BX)	
to 1000 feet	$6 - $10 per foot
to 3000 feet	$10 - $20 per foot

An additional 10 percent to 20 percent of the drilling costs represent mobilization, moving, and site preparation. Appreciable cementing, reaming, casing, standby time, and water haul may add another 30 percent to 100 percent to the cost per foot.

Drilling projects with limited footage (less than 3000 feet) are generally more costly and run from $15 to $30 per foot, including mobilization and moving time from one hole to another.

Access Roads and Trenches

Access roads of several miles or more	
Flat to gentle terrain	$800 - $2500 per mile
Moderate terrain	$2500 - $5000 per mile
Rugged terrain	$5000 - $7000 per mile
Trenching services	
Bulldozer with ripper	$150 - $250 per day plus $15 - $20 per hour for transport time

Underground Exploration Workings

Exploration shaft to 500 feet	
Surface installation	$100,000 - $300,000
Shaft sinking	$300 - $600 per foot
Station cutting	$20,000 - $30,000
Drifting, crosscutting, raising	$70 - $150 per foot

Source: W.C. Peters, *op. cit.*

Table 10

REPRESENTATIVE MINERAL EXPLORATION COSTS IN THE UNITED STATES, 1947-1968

(Developed Properties)

Successful Project (ranked by total cost)	Commodity Sought	Cost of Target Area Examination[a]	Cost of Deposit Evaluation[b]	Total Exploration Cost[c]
1	Uranium	$650,000	$3,918,000	$4,568,000
2	Lead	—	1,134,000	1,134,000+
3	Lead	350,000	650,000	1,000,000
4	Phosphate	300,000	600,000	900,000
5	Copper	100,000	600,000	700,000
6	Copper	—	508,000	508,000+
7	Lead	150,000	350,000	500,000
8	Copper	—	421,000	421,000+
9	Iron	40,000	342,400	382,400
10	"Metal"	—	382,000	382,000+
11	"Metal"	—	310,000	310,000+
12	Phosphate	85,000	200,000	285,000
13	"Industrial mineral"	175,000	50,000	225,000
14	Phosphate	75,000	150,000	225,000
15	Uranium	10,000	200,000	210,000
16	Phosphate	50,000	150,000	200,000
17	Salt	120,000	50,000	170,000
18	Potash	50,000	100,000	150,000
19	Iron	31,700	90,200	121,900
20	Iron	30,000	62,500	92,500
21	Uranium	30,000	50,000	80,000
22	Sand	10,000	60,000	70,000
23	Clay	10,000	50,000	60,000
24	Limestone	10,000	41,200	51,200
25	Uranium	5,000	26,000	31,000
26	Beryllium	5,000	25,000	30,000
27	Uranium	0	28,000	28,000
28	Uranium	0	16,000	16,000
29	Barite	10,000	5,000	15,000
30	Lead	10,000	—	10,000+

[a] Cost from selection of target area to determination of target deposit.

[b] Cost from selection of target deposit to confirmation of its status as an orebody.

[c] Does not include those deposit evaluation costs aggregated with mine development costs.

Source of Data: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

represents a wide range of exploration costs. During this period, total expenditures involved in the examination of target areas ranged from virtually nothing (for a small uranium property) up to $650,000 (for a large uranium property). The median cost was about $32,000. The cost of specific deposit evaluation extended from a low of $16,000 (for a small uranium deposit) to a high of $3.9 million (for a large uranium deposit) with the median about $125,000.

These figures do not present the entire picture, however. These costs do not include the expenses of regional reconnaissance that are not allocatable to a specific project, nor do they include the costs involved in continued exploration carried on throughout the actual development and production stages of mineral resource utilization. Perhaps even more significantly, these costs do not include amounts spent on unsuccessful projects, on the examination of target areas and projects that were subsequently rejected by the exploring firm. Similarly, they do not include those costs incurred in exploring useable mineral properties by firms or individuals other than those that finally developed them.

The cost of examining unusable mineral deposits has also been high, as shown in Table 11, which contains a representative list of the most promising prospects tested and subsequently rejected by firms seeking minerals in the United States during the period from 1947 to 1968. The costs involved in such work ranged from less than $4,000 (for a small uranium prospect) to $900,000 (for a large industrial minerals prospect). The median amount was about $140,000. These, as noted, were only for the most promising targets examined and do not include the costs involved in examining numerous less encouraging prospects that were subsequently rejected.

A study of five minerals firms operating in the Southwestern United States in 1966 showed that they spent nearly $2.7 million in examining 352 target areas and testing 23 specific deposits of which two were considered prospects for mine development.[37] The success ratio of two useable mineral deposits in more than 350 specific area examinations is not unusual in the record of minerals exploration achievement in the United States. While adequate data on the relative successes and failures of minerals exploration activities are not available in sufficient quantity to provide a completely accurate picture of the degree of risk involved in nonfuel minerals exploration, the amount of uncertainty is known to be high. The estimated ratio of uncertainty to expected profit provides an expenditure limit at a particular stage in each exploration project. In essence, the justifiable cost of exploration varies directly with the anticipated value of the discovery and inversely with the odds against making the discovery.

Uncertainty may be primarily a matter of geology, political surroundings, technology, or marketing. All of these will also be operating within the framework of competition for mineral land and for financing. In deciding whether to continue, expand, or abandon an exploration project, a numerical expression for uncertainty can be established on a probabilistic basis, but it is only an approximation, and the guidelines for such approximations are experience and judgement. The allocation of one particular figure to uncertainty demands the simplification of a complex array of risks and objectives. In addition to the clean-cut aspect of completely missing the objective, there are different levels of risk dealing with each part of the objective. There may be, for example, a certain level of risk involving the grade of the expected orebody, another involving the tonnage, and still another dealing with the anticipated cost of mining. There is also the exhilarating chance of finding a much more profitable orebody than expected.

In a few instances, the relationship of an expected orebody to its geologic control is so well-known that a structural projection and a few drill holes will provide enough information to fix the geologic risk. Such is the case in the Witwatersrand of South Africa, where statistical analysis has been particularly successful in establishing ore reserves. In most instances, however, geologic conditions are so complex, and the continuity of orebodies so conjectural, that geology provides the largest element of uncertainty in an exploration program. Geologic uncertainty is, however, expecially sensitive to analysis and must be reconsidered in detail with each new bit of information.

Table 11

REPRESENTATIVE MINERAL EXPLORATION COSTS IN THE UNITED STATES, 1947-1968
(Rejected Properties)

Unsuccessful Project (ranked by total cost)	Cost of Target Examination[a]	Cost of Deposit Evaluation[b]	Total Exploration Cost[c]
1	$ 50,000	$850,000	$900,000
2	446,900	439,900	886,800
3	25,000	570,000	595,000
4	50,000	500,000	550,000
5	100,000	400,000	500,000
6	—	428,000	428,000+
7	—	311,000	311,000+
8	200,000	100,000	300,000
9	50,000	250,000	300,000
10	100,000	191,300	291,300
11	—	279,000	279,000+
12	50,000	200,000	250,000
13	—	243,000	243,000+
14	68,000	134,500	202,500
15	100,000	100,000	200,000
16	50,000	150,000	200,000
17	4,500	182,000	186,500
18	5,000	155,000	160,000
19	4,500	154,000	158,500
20	25,000	120,000	145,000
21	1,500	139,000	140,000
22	9,000	128,000	137,000
23	5,000	123,000	128,000
24	94,000	6,000	100,000
25	17,000	75,000	92,000
26	10,000	60,000	70,000
27	6,000	60,000	66,000
28	16,000	45,000	61,000
29	5,000	48,400	53,400
30	2,500	47,100	49,600
31	17,800	24,700	42,500
32	26,000	14,000	40,000
33	20,000	20,000	40,000
34	25,000	10,000	35,000
35	—	30,000	30,000+
36	10,000	10,000	20,000
37	14,000	6,000	20,000
38	3,000	16,600	19,600
39	10,000	5,000	15,000
40	5,000	5,000	10,000
41	3,200	2,600	5,800
42	2,600	1,200	3,800

[a] Cost from selection of target area to determination of target deposit.

[b] Cost from selection of target deposit to rejection as a suitable prospect.

[c] Does not include regional reconnaissance costs.

Source of Data: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

Political uncertainty, including the dangers of excessive taxation or royalties and extreme restrictions with a change in government, works in the same manner as geologic risk. Even in the most stable of governmental successions, the possibility of a new political attitude within three or four years will have a bearing upon exploration objectives. The Carter Commission, a recent Canadian taxation study group whose recommendations were unfavorable to the mining industry, caused a noticeable postponement of exploration and development plans in Canada until the unfavorable features of the study were clearly rejected by the government and the major political parties.

A high degree of uncertainty, political or otherwise, favors the high unit value exploration target. It precludes the development of a large-scale mine with a long payout period and a large pre-production investment. The payout method of gauging the attractiveness of an investment does not reflect the real long-term profitability of a venture, but the requirement for a short payout period does reflect the level of economic uncertainty. In recent years, accelerating inflation has placed such an element of uncertainty upon the actual value of future profits that the payout period is in considerable use as an index for investment.

Technological uncertainties in a proposed mining operation have a direct bearing on exploration budgeting. Suspected problems in mine development, beneficiation, or rock stability control must be investigated at an early stage in the exploration effort in order to justify the expense of outlining an orebody which demands large-scale or deep mining. Underground exploratory workings and metallurgical test shipments may be required before reaching a decision to risk a major capital investment. Safford and Twin Buttes in Arizona, Pine Point and Endako in Western Canada, and Questa, New Mexico, provide examples of extensive underground exploratory work performed in order to quantify technologic uncertainties.

Marketing of the product involves uncertainties in future metal and mineral prices, changing market specifications, and loss of markets to competitors. A mine plant designed for profitable operation only at full capacity is especially vulnerable. The aspect of market uncertainty is just as critical in exploration decision-making as is the aspect of technological uncertainty. A lowering of the market price or the closing of a custom smelter can wipe out a mine with a marginal grade of ore just as certainly as a unforeseen flow of water.

Quantification of expected profit is based upon some of the same factors as those on the risk side of the profit/risk ratio. The size, position, and grade of an expected orebody are geologic matters which often involve a comparison between the anomaly or occurrence at hand and the characteristics of already known orebodies. Taxation, capital requirements, the margin of profit needed, and the market price are economic factors which also involve comparison with established operations. An exploration target in an uninvestigated geologic area or in a newly established economic environment has a high level of uncertainty and requires a wide spread in profit estimates.

The expected profit is essentially the present value of the total profit to be received over the expected life of an orebody. Since much of the total profit represents income to be received ten or twenty years hence, the time value of money is a major consideration, and present value calculations are frequently involved in exploration and development decisions. The use of a present value calculation in establishing profit guidelines for exploration expenditures has an obvious shortcoming, however. An exact mathematical expression oftentimes hides the inexact nature of its components. "Garbage in, garbage out" is the computer scientist's axiom, and the expression is particularly applicable in minerals exploration. The present value formulae are predicted upon a thorough knowledge of the conditions to be encountered. This situation is most nearly approached in a developed mine and is most remote in a regional exploration effort. In the current era of inflation, maximization of the rate of return on alternative investments is likely to take precedence over the longer term present value consideration. In any event, a projection of costs and market prices over a 20-year period requires broad assumptions. Some organizations, in fact, use the total expected profit from an orebody at today's costs and markets, rather than a present value figure, when balancing profit versus risk for exploration budgeting. Others calculate present value at a "safe" rate of about eight percent rather than a higher risk rate, so that the subsequent discount for risk is not compounded.

Different prospects cannot be properly compared by the unqualified use of profit and risk or uncertainty values. At a prospect in a well-known district with appreciable production from low-grade orebodies, one drill hole in 20 might be expected to lead to the discovery of an orebody with a value of say $400,000. Another prospect might be in a little known area with a recent high-grade discovery. Chances of finding ore in an exploration program could be estimated at one in 500—but the target could have an expected value of $10 million. Under present methods of calculation, the current exploration limit for either prospect would be $20,000, but the reliability of the calculations and the basis for launching an exploration effort would be considerably different.

The repeated use of specific mathematical models in exploration strategy contains many of the same drawbacks as the repeated use of successful exploration techniques. Each objective is unique and each strategy is valid only at one place and one time. Unexpected opportunities and barriers must be dealt with individually. Mathematical exploration models provide for information gained in the weeding-out of targets during a project, but they generally have not been able to quantify the experience and geologic insight gained from earlier unsuccessful projects. In this sense, the losses which are to be balanced against gains in a probabilistic expression are not actually complete losses. They have a value which could be classified as "research" or, better yet, "savvy." In a similar context, exploratory drill holes in a search pattern may be classified at various levels of success in a statistical analysis, but there is also an indeterminate addition to geologic and technologic experience made by each completed drill hole.

6. Exploration Land Requirements

The selection of exploration targets and the money to be spent in their examination also takes into account the growing importance of land use competition. The "highest-order" use of land and natural resources in a given area, as interpreted by the government, may not include a suitable provision for mining and mineral processing. Exploration expenditures for a bulk low-grade deposit suited only to the lowest cost open pit mining may well be wasted in an area with competing urban, recreational, or other uses.

The land required for a target area depends to a large extent on the size and type of deposit being sought. Exploration groups prefer to acquire sufficient land surrounding a target area to ensure space for production facilities if the project is successful. Many target areas contain more than one possible deposit, and continued exploration may lead to another target in the vicinity of the one initially tested. Initial land acquisition is therefore aimed at covering all of the area of potential mineralization plus room for extraction facilities as well as an allowance for miscalculation.

As exploration proceeds, it may become evident that some land areas are unnecessary, and these are dropped, unless option or lease agreements prohibit such action. Some exploration programs, in fact, have been designed to eliminate successive blocks of land as potential ore areas, rather than trying to pick the specific target in advance. These programs are used in very large mineralized areas where selection of the optimum target is difficult.

One to fifteen square miles may be initially staked and/or acquired by other means in large mineralized areas suspected to contain a disseminated copper deposit. Evaporite (e.g., potash, borate, sodium carbonate), gravel, limestone, and phosphate prospects may require smaller or larger areas of land.

In one exploration program for a non-metallic deposit, approximately 200,000 acres of land were acquired initially, and as exploration progressively tracked and narrowed down the best possibilities for ore, the land held was gradually reduced until the final exploration tract amounted to 15,000 acres.

Two or 20 claims (approximately 40 to 400 acres) may suffice for smaller target areas such as a precious metal vein, replacement, or placer deposit. However, most metal mines require more than 40 acres for their facilities and potential mineral-bearing ground under exploration adjacent to their operations.

A representative sample of successful exploration projects completed in the United States since 1947 (see Table 12) indicates an extremely wide range of areas involved in exploration activity. Some uranium prospects required only a few acres of land while exploration for some large industrial minerals deposits covered millions of acres, with detailed target examination and deposit evaluation extending over thousands of acres. The median area involved in reconnaissance was 10,000 acres while the median amount of land used for target area examination and deposit evaluation was 1,000 acres. The median area over the useable mineral deposit was 500 acres, although the arithmetic mean of such areas was nearly 4,000 acres.

A significant portion of the area involved in minerals exploration in the United States is and has been on public lands. A survey of firms actively engaged in domestic nonfuel minerals exploration in 1968 revealed that, since 1947, approximately one-fourth of the land acquired for detailed target examination has been obtained by direct staking on federal lands. For some firms the proportion has run as high as 65 percent while for others it has been as low as two percent. The median firm had acquired about 20 percent of its target areas by direct location on federal land. A slightly higher amount (25 percent) has been acquired by obtaining leases with options to buy either patented or unpatented claims. A total of about 15 percent has been acquired under lease.

7. Time Intervals in Exploration

Time has also been an important dimension in minerals exploration, and one that has been directly related to spatial requirements. The reconnaissance phase of exploration normally requires from one to 12 months or more. This is dependent upon the size and complexity of the region, the data available, and the type and number of target areas envisioned or sought. Generally, several regions are studied at once, off and on, and the office studies are interspersed with physical reconnaissance of the different regions and with specific property examinations. In the field work portion, areas may be selected for generalized geologic mapping with the testing of portions of the areas made by geochemical sampling and/or geophysical methods. This may take from a few days to several months or a year, depending upon the man-power available, the size and complexity of the area, its accessibility, and climate. On the average, one to three months is used.

Land acquisition may precede or succeed the previous reconnaissance phase, depending on the ownership situation and degree of interest in the area. If claims are staked, the location monuments may be constructed in a week's to a month's time. Construction of the other monuments (corner, end-center) is necessarily done within 90 days. If the terrain is rugged and/or pre-existing claims are present, subsequent surveying to adjust the claim boundaries for rectilinearity and provide a precise map of the land situation may take six months or more and will rarely take less than one month. Negotiations for permits, options, or leases may be short or drag out for longer than a year. The application for a prospector's permit from federal or state agencies frequently involves a month's time and can be delayed for several months.

Acquisition of property by any of the methods other than direct staking has in practice involved at least a month's time. Negotiations with the small operator or prospector are frequently, if not usually, less time-consuming than those with other companies or syndicates. The small operator/prospector is normally familiar with the time and cost involved in exploration. Syndicates (groups of people who combine their finances to take a flier at the mining game), particularly those unfamiliar to mining, are often the most difficult with which to negotiate. Terms demanded are likely to be excessive and completely unrealistic.

One syndicate, for example, demanded a $40,000 initial payment on a potential mining

Table 12

SPATIAL REQUIREMENTS IN MINERALS EXPLORATION IN THE UNITED STATES, 1947-1968

Successful Project (ranked by extent of deposit)	Commodity Sought	Total Area Involved in Reconnaissance (acres)	Total Area Used for Detailed Exploration (acres)	Extent of the Developed Mineral Deposit (acres)
1	Salt	—	128,000	50,000
2	Clay	500,000	50,000	24,000
3	Potash	2,048,000	1,280	16,000
4	Phosphate	64,000	32,000	15,000
5	"Industrial minerals"	250,000	32,000	10,000
6	Phosphate	16,000	1,280	8,000
7	Phosphate	3,840	0	8,000
8	Gypsum	640,000	64,000	2,560
9	Iron	102,000	1,580	1,580
10	Gypsum	256,000	1,280	1,280
11	Gypsum	64,000	640	1,200
12	Phosphate	3,000,000	20,000	1,000
13	Lead	50,000	5,000	800
14	Beryllium	3,000	1,200	800
15	Iron	121,000	5,100	600
16	Copper	1,600	800	600
17	Salt	40,000,000	14,000	500
18	Lead	960,000	25,000	500
19	Lead	20,000	1,000	500
20	Copper	4,000	500	500
21	Lead	10,000	4,000	400
22	Gypsum	3,200	100	400
23	Sand	90,000	1,000	300
24	Copper	500	200	150
25	Copper	5,000	500	100
26	Silver-copper	NA	800	100
27	Barite	1,000,000	2,000	80
28	Uranium	5,120	320	80
29	Gold-silver	NA	1,550	80
30	Uranium	150	100	80
31	Copper	500	75	60
32	Limestone	2,500	46	46
33	Uranium	6,000	3,200	20
34	Uranium	5,000	40	5
35	Iron	1,900	90	4
36	Uranium	60	45	4
37	Uranium	3	3	4
38	Uranium	10,000	6	2
39	Uranium	5,000	40	1

Source: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

Table 13

NORMAL LAND AREAS IN MINERALS UTILIZATION IN THE UNITED STATES, 1968

Type of Deposit	Area of Mineralization (square miles)	Area Covering Orebody (square miles)	Area Required for Mining Facilities, Tailings Ponds, Dumps (square miles)
Disseminated (copper, molybdenum, gold silver	5 to 20	1/2 to 2	2 to 5
Flat-lying beds (phosphate, trona)	100 to 1000+	1 to 100	1 to 5
Inclined beds (phosphate, trona)	100 to 1000+	1 to 100	1 to 3
Vein (copper, lead, zinc, silver, gold)	1 to 20	1/10 to 1	1/4 to 2
Sand and gravel	1/2 to 100	1/10 to 5	1/4 to 5
Bedded replacement (copper, lead, zinc)	1 to 5[a]	1/10 to 1	1/10 to 1

[a] Excluding very large Missouri lead and zinc districts.

Source of Data: E. Wisser & Associates

property (having no proven orebodies) in California, followed by more than double that amount at the end of six months, and $4.5 million at the end of a year's time. After six months of attempted negotiations, that property was rejected by the originally interested mining firm. In another case, a small company, subsidiary of a major oil company, offered its mine for a price in excess of $500,000 cash payment. There were no proven ore reserves, and existing ore estimates of this company were made by guess. After negotiations lasting for more than three months, the company acknowledged that it might concede 30 days' time to check reserves. As the time was inadequate to do the job, the property was rejected by the intended purchaser. In contrast, a small miner-prospector was approached for negotiations on his property, part of a major disseminated copper target area in Southern Arizona. Negotiations were initiated and finalized in an evening's time.

Geologically simple target areas may require a few days to a few weeks of study for target selection. Geologically complex target areas, typical of metallic mineral deposits, may require six months or longer, as mapping, geochemical, and geophysical work are done in detail. Actual examination of the exploration target area may take from one month (unsuccessful) to three years (successful, or continued encouragement). Access roads and drill sites must be constructed and sources of water supply determined. If the terrain is rugged or underground drill sites involving lengthy excavation (long cross-cuts or drifts, for example) must be prepared, this phase may last as long as a year, particularly if many drill sites are to be constructed. Generally speaking, however, 30 to 90 days is sufficient for most projects.

Drilling is usually taken in three steps. Initial testing of the target may consist of one to five holes and require one to six months. If the initial data are encouraging, additional drilling to track ore mineral indications and/or to outline the general extent of ore mineralization is done. This may take six months to three years, but usually does not exceed 12 to 18 months. The third step, actual evaluation of the mineral deposit, may take an additional 6 to 18 months.

The duration of exploration projects varies considerably with the amount of drilling done. More than ten holes were drilled on the Mission disseminated copper deposit south of Tucson, Arizona, before Asarco got a significant ore mineral intercept. More than 110 holes were drilled before they were sure they had an orebody. Exploration for the Sierrita orebody, farther south, by the Bear Creek Mining Company lasted three years, during which time 109 holes were drilled, and after which the property was rejected.

Under ideal conditions, target area examination and detailed deposit evaluation could be done in one to two years for a successful exploration project. Most nonfuel minerals exploration projects are unsuccessful, however, and last from six months to a year before being abandoned. From a regional standpoint, companies may conduct exploration programs for many years before finding an orebody. Texas Gulf Sulfur, for example, spent ten years exploring in Canada before discovering their Timmins deposit. Bear Creek Mining Company has been exploring the Western United States for an even longer period and has yet to evaluate a major deposit favorably.

As shown by a survey of active mining firms made in 1968 (see Table 14), the total time required in exploration on successful projects developed since 1947 has ranged from about three months (for a small uranium property) to as long as 30 years (for a gold-silver property). The median time involved, however, has been three years.

Table 14

REPRESENTATIVE TIME INTERVALS INVOLVED IN MINERALS EXPLORATION IN THE UNITED STATES, 1947-1968

Successful Project (ranked by length of time)	Commodity Sought	Time for Target Area Examination[a] (months)	Time for Deposit Evaluation[b] (months)	Total Exploration Time[c] (months)
1	Gold-Silver	240	120	360
2	Lead	60	84	144
3	Uranium	12	120	132
4	Copper	48	60	128
5	Molybdenum	36	60	96
6	Copper-Silver	72	12	84
7	Lead	36	36	72
8	Salt	12	60	72
9	Phosphate	36	24	60
10	Phosphate	36	24	60
11	Lead	24	30	54
12	Limestone	28	24	52
13	Iron	24	24	48
14	Gypsum	36	12	48
15	Uranium	12	36	48
16	Iron	27	21	48
17	Copper	–	36	36+
18	Copper	–	36	36+
19	Copper	–	36	36+
20	Clay	12	24	36
21	Lead	12	24	36
22	Gypsum	24	12	36
23	Gypsum	24	12	36
24	Potash	24	12	36
25	Metal	18	12	36
26	Molybdenum	12	24	36
27	Uranium	12	18	30
28	Copper-Zinc	6	24	30
29	Gypsum	24	6	30
30	Metal	24	6	30
31	Salt	6	24	30
32	Phosphate	12	12	24
33	Beryllium	6	12	18
34	Uranium	12	6	18
35	Barite	12	6	18
36	Phosphate	6	12	18
37	Iron	5	12	17
38	Copper	12	3	15
39	Uranium	8	6	14
40	Metal	6	6	12
41	Metal	6	6	12

(Continued on following page)

42	Industrial Minerals	6	6	12
43	Sand	6	6	12
44	Copper	0	11	11
45	Uranium	2	8	10
46	Uranium	–	4	4+
47	Uranium	–	3	3+

[a] Time from selection of target area to determination of target deposit.

[b] Time from selection of target deposit to confirmation of its status as an orebody.

[c] Does not include that deposit evaluation time aggregated with mine development time.

Source of Data: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

F. CHANGES EXPECTED BY 1985

1. Changing Objectives and Methods

The total amount of land available for minerals exploration has been decreasing as a result of urbanization and other development and federal withdrawals. The total will probably continue to decrease. Nevertheless, demand for mineral products by a more industrialized society has been and is increasing. Mining firms are being forced, therefore, to look not only for mineral deposits which have near-term possibilities of becoming orebodies but also for those deposits which could become orebodies under the proper economic and technologic conditions at some longer-term future date.

In the next two decades, increasing attention will undoubtedly be directed toward exploration for mineral deposits not now of any great economic value, such as many of those containing rare earth metals. As uses and demand are developed for these mineral products or are foreseen by industry, exploration will be directed toward the discovery of potentially economic deposits of such minerals. For example, nickel was in small demand after World War I, but technologic and economic research by the Canadian nickel mining companies developed uses and demand to the extent that nickel is today an essential component of many steel alloys of wide usage, such as stainless steel.

The increasing demand for mineral commodities, requiring more intensive exploration efforts, should cause more and more companies to raise their exploration organizations to divisional or complete subsidiary company status. Foreign-based units operating as subsidiary companies will probably increase in number, if restrictions by foreign countries on American investment are not drastically raised. Many areas of the world outside of the United States contain many more geologically promising areas for potential mineral deposits of higher grade than those currently know to exist in the United States.

The organization of exploration divisions will probably become more complex and diversified as companies broaden their product bases to include a number of different mineral commodities in an attempt to become less dependent upon cyclical changes in demand for any one commodity. Many firms have already done this and may be expected to continue. Kennecott Copper, in addition to its recent attempt at diversification into coal, also has new lead deposits in Missouri. American Metals Climax owns lead and potash as well as molybdenum and uranium mines. Anaconda produces, in addition to copper, aluminum and uranium and has recently discovered a large nickel deposit in Australia. Asarco produces lead, zinc, silver, and copper. Duval Corporation has gone from the production of sulfur and potash to a significant number of non-ferrous metals as well.[38]

With such diversification will come expanded needs for more supporting staff research in basic geology, regional geologic analysis, geophysics, geochemistry, statistical analysis, and future trends in demand for different commodities. All of these will be expanded and probably formalized in specific units within the exploration groups, both at the headquarters and regional levels. Bear Creek Mining Company (a Kennecott subsidiary) has had a statistical analysis group for eight years. Newmont Mining Corporation recently added a computer team to aid in the economic evaluation of mineral deposits. Many other companies are considering, or have begun, the use of computers and statistical analysis in exploration work.

Exploration in the future will rely even more heavily on geology to project, from known data, favorable areas and environments for economic mineral deposits. The use of geophysics and geochemistry should also expand both in regional reconnaissance work and in the examination of specific target areas. Greater use will undoubtedly be made of aerial photography for mapping and regional geologic analysis.

Drilling, as well as surface and underground excavations, will continue to be necessary to evaluate the mineral content and extent of mineral deposits. If more laws are changed to allow drilling instead of surface excavations to validate claims, there should be a marked decrease in the number of trenches and pits dug merely to satisfy location work requirements and a corresponding increase in the amount of useful drilling.

In the future, minerals exploration will be based more on *indirect evidence* of the potential existence of economic mineral deposits as opposed to direct evidence from surface or underground exposures. For example, leached outcrops are even now generally examined for evidence of base metal ore minerals whose occurrence may then be predicted in unleached rock below the surface. If the outcrops contain little or no evidence of having had ore minerals at one time, the area may now be rejected for further exploration. Alteration minerals, however, commonly occur as a halo extending beyond the limits of deposition of the ore minerals in many deposits. Thus, the absence of ore minerals at or near the surface is not necessarily a negative indication. Consequently the trend in exploration is moving more toward consideration of areas which show evidence of minerals which *could be* associated with ore at depth, and to areas in which rock type and structure are *conducive* to mineral deposits, but where direct evidence for them is not exposed.

A recent example of the use of geological theory is the Kalamazoo disseminated copper orebody, recently discovered after testing of the geologic hypothesis that faulting had displaced, rather than limited, a part of the nearby San Manuel orebody. The area overlying the Kalamazoo orebody is partly covered with rock formations deposited after the ore had been deposited, and there is little in the way of surface exposures to indicate the presence of this orebody other than weak rock alteration and sparse iron oxides. Examples of completely hidden orebodies are found along the Viburnum Trend in Southeast Missouri, where deposits of lead sulfide are overlain by more than a thousand feet of barren sediments. Only geologic theory originally indicated the presence of the Viburnum deposits.

With further successful efforts such as those which yielded the Kalamazoo and the Viburnum deposits, more and more emphasis will be placed on locating theoretically favorable areas, supporting and/or confirming their favorability by geophysical and geochemical surveys where applicable, and then testing them by drilling. Many of these areas will be partly to completely lacking in existing surface exposures indicative of the presence of mineralization. Many of these will be areas now classified as "not mineralized."

Despite increased exploration in new areas, old, abandoned mining districts will continue to be combed over, analyzed, and subjected to renewed exploration on targets determined by the development of new information and concepts of ore occurrence. This is being done even now, and has been for some time. For example, until a few years ago, mining in the Silverton-Telluride area in the San Juan Mountains of Southwestern Colorado was confined to veins in volcanic rocks. Recent exploration disclosed that ore occurred in and adjacent to veins which extended downward into the underlying older sedimentary rocks. New orebodies were found and will probably continue to be found as exploration efforts further test this hypothetical potential for ore adjacent to other vein structures that extend down into these older rocks.

Prior to the discovery of the Pima copper mineral deposit in the Twin Buttes mining district south of Tucson, Arizona, the district had been considered mined out. Since the discovery in the early 1950's, four major new disseminated copper orebodies (Esperanza, Mission, Sierrita, and Twin Buttes) have been found and are either in production or are being developed for production. All of this has occurred in the last 15 years, and similar events may be expected in the next 15 years.

At present, preliminary studies are made of target areas to see if they are large enough to contain an orebody of suitable size for the company involved, and if the geologic and topographic environments are suitable for envisioned mining methods. Different firms have different requirements as to the size, type, and grade of orebody they are willing to mine. These requirements reflect the degree of skill and flexibility of the firm and its ability to handle diverse mining, metallurgical, and marketing problems as well as the degree of risk which the company is willing to assume, the profit return which it requires, and the amount of capital it can command.

Some of the largest companies are willing to take high risks on low-potential profit returns while others of the same size are ultra-conservative. Although large companies generally consider small mineral deposits wasteful of their time, manpower, and financial assets, exceptions do exist. Uranium orebodies are generally smaller than base metal orebodies, yet Anaconda, Phelps Dodge, New Jersey Zinc, and American Metals Climax have all found it profitable to be in the uranium business as well as in base metals. Conversely, some of the smaller mining companies aim their exploration at very large deposits.

Over the next two decades, the physical, economic, and technical factors requisite to defining suitable mineral deposits for individual firms will become the subject of more extensive and more refined study. Mathematical simulation of the effects of different variables on the suitability of target areas and specific mineral deposits is expected to be developed and used more extensively as a basis for management decisions. These refined approaches, made feasible by the use of computers, may also come into use by local and regional exploration offices in their evaluation of deposits and target areas of different mineral commodities. Nevertheless, the key to successful exploration will contnue to be accurate *interpretation* of all the data available.

Various sources of data may not only supply computers to calculate ore reserves but also to analyze the evidence of mineralization and project the direction in which further exploration should proceed. Statistical analyses, too lengthy to be done manually within any reasonable time, can be programmed into a computer and the results gotten in a few minutes' time. The interpretation of geophysical and geochemical data will become increasingly dependent upon the use of computers as they permit the weighting of different factors affecting interpretation to be analyzed rapidly and concurrently.

2. New Exploration Techniques

Advances in the use of sensory exploration tools, including infra-red photography, radioactive detection, and the various other geophysical methods now in use, may be expected by 1985. Completely new methods and equipment may also be devised.

Certain types of metal deposits are produced by events and features which are associated with large amounts of heat. Although produced millions of years ago, such bodies may still be cooling today and the remaining flow of heat may be measurable. No reports have been made of the discovery of orebodies by thermal measurement methods, but they are assuming greater importance as the possibilities of hyperaltitude measurements from satellites become real. Considerable research, however, will be necessary to evaluate these methods and their ultimate usefulness.

All rock and soil formations are radioactive to some extent because they contain minute quantities of elements that are radioactive. Some formations are characteristically more radioactive than others. Acid igneous rocks, particularly volcanics, are usually more radioactive than either basic rocks, sandstone, limestone, or salt formations. Using airborne detection equipment, petroleum and uranium exploration teams have been able to outline areas and rock types favorable for exploration. Airborne radiometric work has also been useful in broad regional mapping of different rock types.

Recent research has been directed to the development of equipment which can distinguish different types of radioactivity that are characteristic of certain elements. It seems likely that airborne methods will be developed to distinguish areas of rock rich or deficient in various types of radioactive elements. Thorium, for example, is a radioactive element of considerably less current economic importance than uranium. The distinction of thorium-bearing areas from uranium-bearing areas by airborne radiometry would be of great value in exploration. Certain minerals preferentially trap certain radioactive elements. Fluorite not uncommonly contains small amounts of uranium, and a uranium-specific radiation detector could help locate fluorite deposits as well as those of uranium.

A term that was apparently born with the Space Age, *remote sensing*, refers to measurements made of the earth by a sensor mounted or carried at a distance from the object measured. In a real sense, many geophysical methods described above are remote sensing methods, particularly those that are airborne. The term, however, is now more specifically applied to certain methods of measuring the properties of the earth from very high flying aircraft or orbiting spacecraft. Many of the extremely remote sensing methods now in use are the result of research by the defense and aerospace establishments, but they offer significant possibilities as techniques useful for mineral exploration. Although these methods and their applications are in infancy in terms of development, a major program of research is presently being carried out by NASA and other government agencies to assess their use in an Earth Resources Survey Program (EROS).

Remote sensing techniques measure a property of the earth's surface, or in a few instances, an unknown but probably slight thickness of the upper surface. Among the properties measured are color or tone, properties related to thermal conductivity or heat constants, ultra-violet reflectivity, and the response of surface materials and forms to radar. All of the measurements may be carried out from aircraft at very high altitudes or from orbiting spacecraft.

Historically, the first remote sensing results were probably those of black and white photography from aircraft. This technique must certainly stand as one of the most valuable aids to geological exploration and mapping ever devised. Black and white photography is carried out on an extremely wide scale today and is used the world over. It serves as the base from which most topographic maps are now prepared. The use of color-sensitive films was a natural corollary, and colored aerial photographs are extensively used today in exploration for certain types of mineral deposits.

The advent of the spacecraft provided a new and spectacular plateform for photography, and some of the first photographs to draw the attention of mineral exploration staffs were the infra-red photographs taken in the Viking Rocket Program in 1955. These photographs looked at a great part of the Southwest and, for the first time, major geological features were observed.[39] As orbiting spacecraft became operational, a tremendous amount of such data became available. Data were returned from both manned (Mercury, Gemini, and Apollo) spacecraft and unmanned (Tiros) satellites. This information included both colored photography and infra-red images. Airborne radar (AR) and infra-red imagery developed as military surveillance tools, but the results have also been of some use in geological mapping and minerals exploration. Commencing with the Mercury Program, hand-held cameras were used to photograph both features and regions of interest on the earth's surface.[40] These photographs, all on colored film, have yielded to study, and gross geologic features have been identified and studied. Published results of these studies have underscored the significant extent to which the photographs may be used for mapping purposes. Much, however, remains to be determined from an analysis of the colors on the photographs and their significance.[41] Over the next decade it can be expected that such analyses will be made.

Infra-red emission provides more information on rock composition than is obtained on common black and white film. As all substances emit infra-red radiation, they can be detected by a sensor and an image constructed of these emissive characteristics. Much of this information may be related to rock composition or to rock structure. Geologic interpretation of infra-red data has scarcely begun and much additional work is necessary before a meaningful evaluation of the technique can be made.

Radar images taken from high-flying aircraft also reveal a different type of information than that seen on conventional aerial photographs. A system mounted in an aircraft scans perpendicular to the aircraft's direction of travel and builds an image that reveals a considerable amount of structural geologic information. An assessment of the method has been presented by Gillerman,[42] who concluded that in regions of volcanic rocks, the high glass content of those rocks enhanced radar wave response. An assessment of the method as a geologic tool to solve specific problems has been presented by Cooper,[43] who was able to discern and map hitherto unrecognized geologic features such as unknown outcrops of volcanic rocks and a buried flood plain.

A variety of other remote sensing methods have been proposed.[44] Few of these, however, have been tested and many have been evolved specifically for the study of atmosphere-free objects in space. There are, however, many of these methods with strong potential for minerals exploration here on earth, and these simply await testing. If economic and political conditions are favorable, such testing will undoubtedly come soon.

Research in geophysical methods and their application to problems of minerals exploration has barely kept abreast of the demands placed on them during the past 25 years. Several factors, however, will control the direction and ultimate usefulness of such prospecting methods during the next several decades. Foremost is the nature of the minerals being sought. An examination of the trend of mineable grade for certain metallic ores shows that lower and lower grades are being extracted at a profit. For example, in 1935, ore grades well in excess of one percent copper had declined to around 0.8 percent by 1955. The significance of this trend in terms of the application of geophysical methods to minerals exploration is that the type of rock being sought now and that will be sought in the future is becoming less anomalous in the context of geophysical response. The rock types that make up the orebodies are becoming more like the average rocks of the crust. As a consequence, the response of such mineral deposits to measurement will more closely approximate that of the rocks which surround them and they will not present the contrasting image of the more anomalous rock bodies found in the past.

The techniques of geochemical prospecting have evolved rapidly in this country over the past twenty years and are still in a state of evolution. Based upon the nature of the method, it is possible to make some predicitions as to what may evolve in the future. As with geophysical methods, the tendency in geochemical exploration is toward sophistication in the analytical treatment of the data obtained. It is now possible to rapidly and cheaply analyze natural materials for their chemical content. The major problem still confronting the use of newer geochemical method is that of data interpretation. This problem of interpretation will probably be approached along several directions of continued research over the next two decades.

The acquisition of additional data on a region-wide basis will become increasingly necessary to gain an enhanced understanding of the distribution of trace elements under all conditions of climate and soil type. This approach to the research will involve a major amount of basic field work and analysis.

Continued and expanded use of the computer will allow a greater degree of flexibility in interpreting information. At the present time, only three or four elements are studied in the great preponderance of prospecting programs. With the development of computer programs to accommodate and analyze the information, it will probably become possible to examine a great number of potentially useful elements and ratios that are not now studied because of the weight of the data and the corresponding inability to absorb and analyze it.

It is extremely likely that methods of chemical analysis will become even more simplified and routine than those now in use. There is some evidence of this even now. A field instrument that can make a nondestructive analysis for certain elements exists in the form of a portable x-ray fluorescent analyzer. Considerable continued development is necessary before such instruments find their way into common use, but the prospects for the future are bright.

Thus, continued research into distribution of the elements in natural materials, continued research into means of data interpretation, and the continued sophistication of chemical analytical techniques are certain to contribute to future geochemical exploration. But less complex and less sophisticated techniques will also remain useful in the future search for minerals. The miner's pan has been, still is, and will probably continue to be an extremely useful tool in detecting heavy mineral anomalies.

As valuable mineral deposits become harder to find, even though exploration methods become more sophisticated, it is expected that the *time* involved in minerals exploration for any one deposit will lengthen. As larger, disseminated deposits become more important, it is also likely that the *areas* involved in exploration will become larger. And along with everything else, the *cost* of minerals exploration will continue to rise.

Fig. 18 - Diamond drills and other equipment used in minerals exploration may be expected to continue to increase in sophistication and cost. But the quality of information obtained about unseen mineral

FOOTNOTES

1/ T. A. Rickard, *A History of American Mining,* New York: McGraw-Hill Co., Inc., 1932.

2/ J. J. Jakosky, *Exploration Geophysics,* Los Angeles, California: Times-Mirror Press, 1940.

3/ E. de C. Clark and H. A. Ellis, "Metasomatism of Country near Orebodies and Its Possible Economic Significance," *Economic Geology,* Vol. 34, 1939, pp. 777-778.

4/ G. M. Butler, *Some Facts About Ore Deposits,* Tucson: University of Arizona, 1935.

5/ T. A. Rickard, *op. cit.,* p. 111.

6/ L. E. Preston, *Exploration for Non-ferrous Metals,* Washington, D.C.: Resources for the Future, Inc., 1960, p. 79.

7/ *Ibid.,* p. 79.

8/ C. Stoddard and J. Carpenter, *Mineral Resources of Starey and Lyon Counties, Nevada,* Nevada State Bureau of Miners, Reno, 1950, p. 21; H. Barger and S. H. Schurr, *The Mining Industries, 1899-1939,* New York: National Bureau of Economic Research, Inc., p. 119.

9/ T. A. Rickard, *op. cit.,* p. 111.

10/ W. H. Emmons, *Enrichment of Ore Deposits,* U.S.G.S. Bulletin No. 625 (1917), pp. 55-56.

11/ T. A. Rickard, *op. cit.,* p. 111.

12/ C. Stoddard and J. Carpenter, *op. cit.,* p. 22.

13/ U. S. Bureau of Mines, *Information Circular 8252.*

14/ C. Stoddard and J. Carpenter, *op. cit.,* p. 23.

15/ *Ibid.,* p. 23.

16/ T. A. Rickard, *op. cit.,* p. 81.

17/ *Ibid.,* p. 81.

18/ *Ibid.,* p. 85.

19/ *Ibid.,* p. 87.

20/ M. S. Reford and J. S. Sumner, "Aeromagnetics," *Geophysics,* Vol. 29, 1964, pp. 482-516, and Hansen *et al, Mining Geophysics,* Vol. I, *Case Histories,* Tulsa: Society of Exploration Geophysicists, 1966, p. 492.

21/ J. S. Sumner and A. B. Schnepfe, "Underground Gravity Surveying at Bisbee, Arizona," *Mining Geophysics,* Vol. I, Tulsa: Society of Exploration Geophysicists (1966), pp. 243-251.

22/ S. H. Ward *et al,* "AFMAG-Applications and Limitation," *Geophysics,* Vol. 31, 1966, pp. 576-605.

23/ W. E. Heinrichs, "Geophysical Investigations, Ore Know Mine, Ashe County, North Carolina," *Mining Geophysics,* Vol. I, *Case Histories,* Tulsa: Society of Exploration Geophysicists (1966), pp. 179-184.

24/ G. R. Rogers, "An Evaluation of the Induced-polarization Method in the Search for Disseminated Sulfides," *Mining Geophysics,* Vol. I (Hansen *et al,* eds.), Tulsa: Society of Exploration Geophysicists, 1966, pp. 350-356.

25/ *Ibid.,* p. 356.

26/ P. G. Hallof, "The Use of Resistivity Results to Outline Sedimentary Rock Types in Ireland" and "Induced-polarization and Resistivity Results from the Cactus Deposit, Miami, Arizona," *Mining Geophysics,* Vol. I (Hansen *et al,* eds.), Tulsa: Society of Exploration Geophysicists, 1966, pp. 18-27 and pp. 306-312.

27/ Lloyd O. Bacon, *Refraction Seismic Case Histories in Mine Geophysics,* 1966, pp. 105-113.

28/ Erland Grip, "Tracing of Glacial Boulders as an Aid to Ore Prospecting in Sweden," *Economic Geology,* Vol. 48, 1952, pp. 715-725.

29/ H. E. Hawkes and J. S. Webb, *Geochemistry in Mineral Exploration,* New York: Harper and Row, 1962, pp. 91-113.

30/ *Ibid.,* pp. 324-326.

31/ H. E. Hawkes, *Principles of Geochemical Prospecting,* U. S. Geologic Survey, Bulletin 1000-F, 1957, pp. 225-355.

32/ H. E. Hawkes and H. W. Laken, "Vestigial Zinc in Surface Residuum Associated with Primary Zinc Ore in East Tennessee," *Economic Geology,* Vol. 44, 1949, pp. 286-295; and H. L. Cannon, "The Development of Botanical Methods of Prospecting for Ore Deposits," *Science,* Vol. 132, 1960, pp. 541-598.

33/ Duncan Derry, "Exploration Targets and the Choice of Weapons," *Mining Magazine* (March 1969), Vol. 120, No. 3, p. 153.

34/ Harrison Schmitt in "On Mapping Underground Geology," *Engineering and Mining Journal,* Vol. 137, 1936, p. 557, as quoted in McKinstry, p. 1.

35/ H. E. McKinstry, *Mining Geology,* New York: Prentice Hall (1948), p. xv.

36/ *Ibid.,* p. 205.

37/ A. J. Perry, *Organization and Costs for Mineral Exploration in the Southwest U.S.A.,* Tucson: The Superior Oil Company, 1968.

38/ "Where Copper is Not Quite King," *Business Week* (December 7, 1968), pp. 104, 108.

39/ T. W. Mitcham, "Viking Rock Photograph of Arizona, California, and Northern Mexico, West of Tucson, Arizona," *Arizona Geological Society Guidebook II,* Tucson: Arizona Geological Society, 1959, pp. xiv-xix.

40/ P. D. Lowman, *Geologic Orbital Photography; Experience From Gemini Program,* Goddard Space Flight Center, Publication X-644-68-228, 1968, p. 34.

41/ S. R. Titley, "SouthernArizona - The View From Gemini," *Arizona Geological Society Guidebook III,* Tucson: Arizona Geological Society, 1968, pp. 1-6.

42/ Elliot Gillerman, *Investigation of Cross-Polarized Radar on Volcanic Rocks,* Research Report No. 61-25, University of Kansas, 1967, pp. 1-11.

43/ J. T. Cooper, "Geologic Evaluation - Radar Imagery of Twin Buttes Area Arizona Test Site 15," U. S. Geologic Survey, Technical Letter, NASA-28, 1966, p. 4.

44/ P. C. Badgley, Leo Childs, and W. L. Vest, "The Application of Remote Sensing Instruments in Earth Resource Surveys," *Geophysics,* Vol. 32, No. 4, 1967, pp. 583-601.

CHAPTER 8

MINERAL DEPOSIT DEVELOPMENT

Have changes occurred in the technical and economic characteristics of mineral deposit development since the 1860's? What factors have influenced any such changes? Have any such changes since 1947 followed discernible trends which might be projected to 1985?

A. THE DEVELOPMENT PROCESS

1. Components of Mine Development

For the most part, the general public does not seem to be aware of the complexities that attend the transforming of a mineral deposit into a mine. Rather, many people appear to believe that once a discovery of a valuable mineral deposit is made, miners simply gather up the treasure, receiving the reward for the find as they would receive a gift. In reality there are several complex stages in the creation of a mining enterprise. These proceed from exploration through development and culminate in the production and sale of a useable mineral commodity, as shown in Table 15.

Although the work entailed in some of the stages in the creation of a mine is fairly distinctive, the work in others is sometimes very similar or even identical. Exploration involves the search for mineral deposits and may utilize some or all of the tools and techniques previously described. Probably the greatest problem in this first stage is determining when or even if a discovery of any significance has been made. Evaluation then involves examination of the "discovery" in light of the technology and economics of the time and place to determine the potential for the success of the deposit as a mine. At this point several questions have to be answered positively or further work on this property may be abandoned. Is the geologic setting such that the valuable mineral discovered is likely to occur in sufficient quantity and grade to justify further investigation? Is it likely the deposit can be mined and treated at a profit? Is the supposed "ore" amenable to concentration and other treatment?

Many other factors must also be taken into consideration. These include total supply and demand for the mineral commodity found, market location, labor conditions, government policies, and taxation, and all must be considered before a decision can be reached to invest further in a mineral property.

Deposit evaluation, like more preliminary exploration, involves search, but the objectives are different. The objective of initial exploration is to make a "discovery," while the objective of evaluation is to ascertain what has been discovered. In this stage the deposit should be delineated; the grade of the ore ascertained; bulk samples taken for laboratory testing and subsequently for pilot plant testing; and the physical properties of the ore and rock determined. At each stage, all of the questions that were raised in exploration must be answered again in the light of new and better information before the "discoverer" can afford to risk the very much larger amount of capital required for mine development.

Mine development is the preparation of an orebody for mining. In a deeply buried orebody, shafts have to be sunk to reach the ore, haulageways have to be driven, and certain other facilities have to be installed. In a proposed open pit, the overburden must be stripped away to expose ore, benches must be established, and haulage roads established. Plant construction, actually a part of the development phase, usually begins soon after mine development proper starts and is sometimes completed, for the most part, before all of the primary mine development is complete. Completion of the major plant facilities may coincide with completion of the last development work that gives final access to the ore

Table 15

THE CREATION OF A MINE

	Stage	Cost[a]	Time[a]
1.	Reconnaissance	Less than 1 unit	1 to 20 years
2.	Examination and Evaluation	up to 5 units	1/2 to 3 years
3.	Mine Development	30 units	2 to 5 years
4.	Plant Construction	80 units	2 to 3 years
5.	Initiating Production	7 units	1 to 6 months
6.	Production, with continuing exploration and development.		

Source: Modified after Table 1 in *The Making of a Mine*, Circular 41, by John E. Allen, New Mexico Bureau of Mines and Mineral Resources, 1956.

[a] These are to be regarded as very rough approximations. Costs are in relative units.

deposit, although much of the early development may be done with a temporary plant. Such a plant is seldom of sufficient capacity or reliability, however, to sustain any appreciable volume of production on a continual basis.

Plant facilities normally include such major items as maintenance and repair facilities, utilities for the distribution of electricity, water, and (often) natural gas, warehouses and storage yards, change houses, and offices. An underground mine requires a substantial investment in ore bins, hoisting facilities, and compressed air equipment. All but the smallest high-grade operations will require a mill and concentrator for mineral beneficiation. Large operations, both open pit and underground mines, frequently require the construction of a spur railroad line and ore loading facilities.

The final stage in the creation of a mine, initial production, is a major operation in mining because much of the equipment is custom-built and has not experienced the long debugging history that the usual production items have. Mining equipment systems are often unusual, if not unique, and the same applies to the many variations of actual mining methods used. Even though tons of bulk samples have been run through a pilot mill, an initial full-scale mill operation invariably experiences many problems before it can achieve full production at its designed capacity.

The values of the relative cost units referred to in Table 15 vary considerably with the type of mineral deposit and the scale of operation. For small, high-grade deposits requiring no milling or special processing before marketing, the value of the unit may be as low as $5,000. For larger, lower-grade deposits, a unit may range from $10,000 to $50,000 and, for the vast porphyry copper and molybdenum deposits and for some of the bigger iron deposits, it may reach one million dollars or more.[45]

An important element in the initial cost picture is the abruptly increasing costs that come to bear in the development and plant construction stages of mine creation. This points up the very critical need to do rather thoroughly and carefully the work of the exploration stages. Additional money spent in examination and evaluation might very well indicate that the property is submarginal and its development should be abandoned or postponed. At this stage, the maximum investment to be lost would be minimized. By cutting corners in the examination stage, however, a project may continue all the way to the production stage before it is ascertained to be uneconomic. At this point the loss might well be 18 to 20 times as much as the maximum loss that might have been incurred if a few more holes had been drilled and a few more assays made in the exploration stages.

Unfortunately, at whatever point in time the main work of initial exploration must cease, there will always be a finite probability that the ore reserve estimation will be substantially in error. Most of the work of exploration is not productive in terms of enabling or hastening production. Therefore, this kind of "unproductive" work cannot be carried on indefinitely. Obviously, more should not be spent in the exploration drilling of an orebody than can be recovered in profits from its utilization.

Actually, the work within each of the several stages in mine creation is seldom if ever completely terminated before the next phases begin. For example, the initial exploration of a deposit may block out 100 million tons of ore or a 10 year reserve at an annual production of 10 million tons. A subsequent exploration program may block out 50 million additional tons of ore by the time 60 million tons of the originally blocked out orebody have been mined. This serves to extend the life of the mine at this point from the four years remaining to nine years. Thus, if additional ore is to be found, subsequent exploration after initial development may and frequently does extend the life of any mine substantially.

2. Types of Mine Development

In underground mining (and to a certain extent in surface mining), there are two distinct types of development: (1) primary or general mine development, and (2) secondary or stope development. Primary development consists of sinking shafts, cutting shaft stations, driving haulageways, making ventilation raises, sumps, pumprooms, fan installations, and other facilities required for the general operation of the mine. The openings excavated in primary development are the more or less permanent openings that serve as major supply routes for the life of the mine and provide access to the orebody as a whole. In contrast, secondary or stope development comprises smaller openings, such as raises, drifts, and cross-cuts, that usually have a relatively short life and are designed to provide access to particular portions of the orebody from which mineral is being removed at any one time. Some ore is, of course, produced during development, but this is only a small portion of the whole. The primary function of development is to prepare the orebody for volume mining.

While a great deal of general or primary mine development must be performed before production begins, both primary development and secondary stope or bench development normally continue even after production has started. This is necessary because, as individual stopes or levels become mined out, new ones must be developed to maintain a desired production rate. Also, from a capital investment standpoint, it is desirable to begin recovering capital as quickly as possible (i.e., commence production quickly) rather than investing vast sums to complete development before beginning production. Even more important, the physical realities of a mineral deposit and the technical realities of mining methods simply do not permit the complete development of an orebody before the commencement of production.

Development in surface mining involves primarily the work required to expose the ore and make it accessible for mining. This entails the initial stripping away of part of the non-ore overburden to expose a sufficiently large expanse of ore that will afford enough working room to permit the desired ore production. The amount of overburden that must be removed before ores can be produced is minimal if the orebody outcrops or is exposed at the ground surface. On the other hand, if the top of the orebody is significantly below the ground surface, development can entail the stripping of many millions of tons of waste materials.

Just as underground mine development requires the excavation of openings on one or more levels, so also in surface mining, benches, commonly 30 to 50 feet in height, are excavated in order to carry on the development in an orderly and safe manner. The haulageway or main ramp either spirals or switchbacks up the slopes of the pit on grades which vary depending on whether rail or truck haulage is used.

Another important part of open pit development is the preparation and construction of dumps for the disposition of waste rock resulting from overburden removal and beneficiation processes. Nearby valleys, canyons, and hillsides are usually excellent sites for waste storage, but if none of these features are available, dumps must be built up, sometimes to heights of 200 feet or more.

Other mining methods, e.g., placer mining, solution mining (including the Frasch process mining of sulfur), and different methods of beneficiation, require somewhat different methods of development. Nevertheless, mine development, or the development of a mineral deposit for mining, basically involves the exposure by one means or another of the orebody or appropriate parts of it, in a manner that will permit the subsequent removal of ore material in volume. Development also involves the installation of necessary equipment and facilities to be used in the removal of ore from the earth.

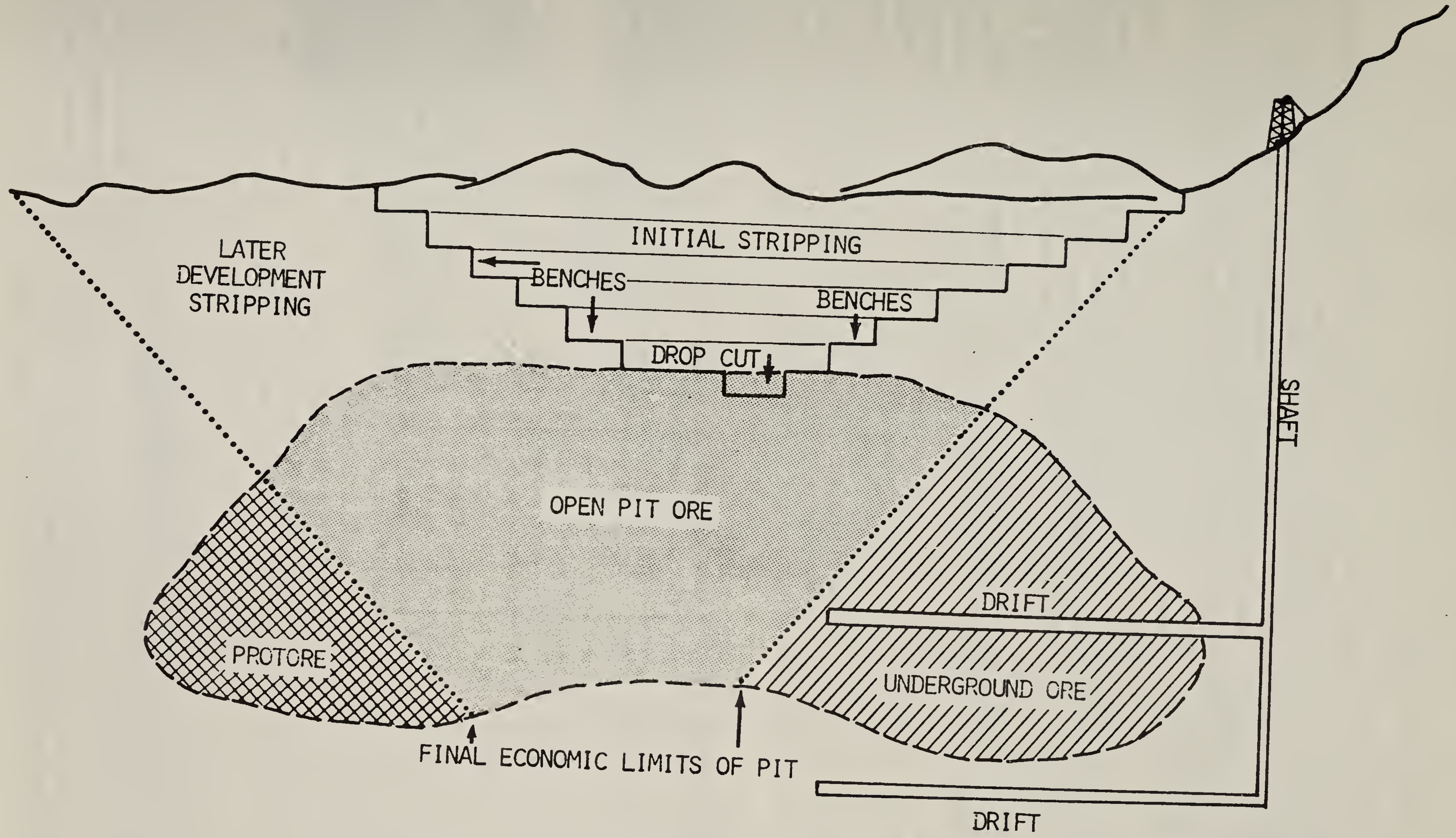


Fig. 19 - Representation of the development work necessary for the mining of a large disseminated orebody by both open pit and underground methods. The area labeled "protore" while it might be identical mineralogically with the "open pit ore" is covered by too much overburden to be mined economically by surface methods and is too small to be mined by underground methods.

B. DEVELOPMENT METHODS IN THE 1800's

1. Placer Mine Development

It would be an oversimplification to say that the year 1860 marked a noticeable change in mining methods used in the United States. That there was a change in emphasis, however, is apparent from an observation in the *Mining and Scientific Press* of San Francisco, July 7, 1860, that the advance to date of mining technology had been in three stages. First, there had been the mining of placers in the beds of rivers, creeks, and gulches, followed by the mining of leads in former water courses. But in 1860, the new mining had become that of quartz and hard rock.

Yet the new hard-rock mining was still in its infancy as far as the United States was concerned and it was to remain so until emigrants of one kind and another, and especially the Cornish, transferred the mining techniques of Europe to the new environment. It was in the United States that the most startling innovations in mining were to take place, but even so, placer mining still occupied much attention and was to continue to do so, as long as placers were to be found.

The first gold placer miners reached the placer sands by digging, often to the bedrock, and scooping out pits which, in a sense, resembled present day strip-mines in miniature. This form of development involved the removal of a tremendous amount of useless overburden. Sometimes the early placer miners would venture to undertake "coyoting," i.e., digging a shaft down to the gold-bearing sands and then drifting outwards into the deposit through a series of tunnels until the entire operation took on the appearance of the spokes of a wheel. Initially, there was little experience in timbering these shafts, and cave-ins were not unusual. In the 1890's this method was used almost entirely in the Yukon, for it was warmer than open pit placering, while the perma-frost supported ground so that there was little need for timbering.

Although in early mining the gold was initially extracted from the sand by panning, a simple hand process, the later introduction of methods involving sluices required the construction of some rather elaborate systems of troughs and flumes in the development of placer deposits. In 1861 the *Mining and Scientific Press* quoted the case of a man named Welch of Indian Hill in Sierra County, California, who possessed more than 2,000 feet of rock sluice on his claims.

Hydraulic mining was the technique devised to tackle the alluvial placer deposits in abandoned river beds. Its methods were certainly being tried out as early as 1851 and were to continue throughout the century and beyond. In developing a deposit for hydraulic mining, the miners would first locate a promising gravel bank and then, at a high point, construct a dam across the nearest stream. The head of water thus created was then transported by a large iron pipe down to the foot of the gravel bed and ejected at the gravel bed through a nozzle, sometimes called a *monitor,* but more often a *giant.* The backwash was screened and channeled through a natural sluice system, cut out of the bedrock, or through wooden sluice boxes.

Placer mining, of course, demanded a tremendous abundance of water. In developing placer deposits, new and more elaborate water-courses had to be constructed to meet the required pressures to work the giants and other early equipment. Water companies were organized to meet the demand for this highly specialized work and proceeded to build a network of flumes, canals, and aqueducts around the sides of mountains and over gulches. Not always were the relations between the water companies and the miners amicable, with disputes arising constantly over water charges. The situation was similar in placer districts outside of California. In reporting on new gold placer developments in Northern Colorado and Wyoming, *The Engineering and Mining Journal* of August 3, 1895, reported that about 200 fortune hunters were prospecting and surveying the area, though they all too well realized that their major worry was the provision for water, for "many a man has to spend one million dollars on ditches alone before turning a single wheel."

The most sophisticated form of placer mining, already in existence by the 1890's in a highly developed stage, was the steam dredge, of which there were two kinds. The California type of bucket dredge floated in an artificial pond which moved with it as the ground before it was excavated and then deposited behind the dredge. On board and arranged on two decks (for it was really a land-ship) were the usual gold recovery tables. This type of dredge was much used in Alaska and the Yukon, where the gravels had to be thawed out with water before they could be dredged.

The other type of dredge used in the 1800's was known as the dragline dredger. It was really a combination of dredge and dragline excavator, such as is now used in strip-mining for coal and pebble phosphates, and was used in the excavation of the Panama Canal. The washing plant, consisting of hopper, revolving trommel, gold recovery tables, pumps, and stacker, was carried in a hull, again floating on its own pond, while a dragline excavator, working from the shore and anchored to the nearest tree, dumped the gold-bearing gravel into the washing plant.

The initial development costs of this kind of mining were, of course, relatively high, but the overhead was extremely low and the machines could handle a phenomenal amount of gravel. But, like the awkward automaton it looked and was, it was virtually helpless when the gravels were finished or it came to solid rock. It could not be turned or navigated to another position, so it was usually unceremoniously stripped of its machinery and the hull left to rot, as became the fate of many abandoned in the creeks of the West.

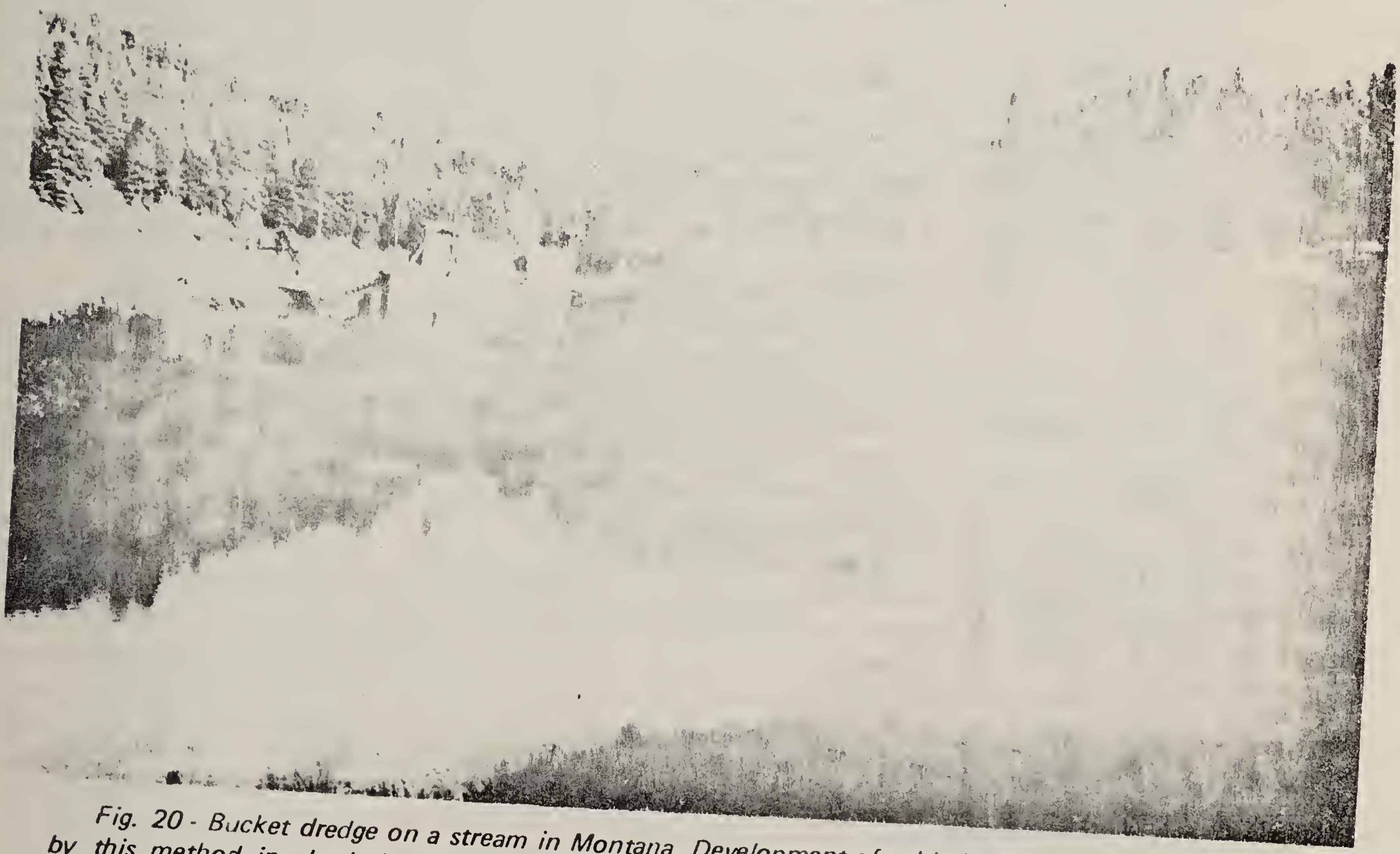


Fig. 20 - Bucket dredge on a stream in Montana. Development of gold placer deposits for early mining by this method involved the construction of a pond large enough to float the dredge and the on-site assembly of the equipment. The dredge was really a combination of mining and beneficiating plant.

2. Underground Mine Development

But it was, of course, in the development of hard-rock mining that the most spectacular innovations occurred in the United States after 1860, introducing techniques virtually unknown in the West but of ancient stock in Europe. These new methods led to changes in the mining laws that had as yet only taken account of conditions in the placer fields and were inadequate to cover the unknown underground. Based on the general belief that the discoverer of a vein owned it all the way down as far as it went into the earth, no matter how deep and broad, the early mining law of the 1860's elaborated the principle that whoever held the apex held all, a principle that led to endless apex litigation.

The discovery of hard-rock lodes in the Western United States is traditionally associated with the finding in 1859 of a gold-quartz lode by John H. Gregory in the gulch that was named after him near Central City, Colorado, and with the discovery of the Comstock silver lode of Western Nevada in the same year. As yet there was no real native skill and experience in the American West that knew how to win the ore from the ground except by the antiquated methods of the Mexicans who had settled in California. When in 1847 Barron, Forbes and Company took over the New Almaden quicksilver mine near San Jose, California, the underground workings consisted only of an adit and horizontal entrance about 25 feet through the rock. The ore was mined without system through tunnels driven into the hillside with small *raises* or *winzes* that followed the inclination of the cinnabar occurrence or by shallow shafts that were no more than circular holes in the ground, provided with notched timbers up and down which the Mexicans clambered, bringing the ore to the surface on their backs in rawhide baskets.

That there was a need for information on the best way to sink a shaft is clear from the *Mining and Scientific Press* of November 1860, for it published two articles on the subject. In metal mines, it was observed, shafts were rectangular and divided generally into two portions by a casing of woodwork which separated the parts where the buckets for hoisting the ore passed up and down from that in which the pumps were placed and where the men ascended and descended. Several modes of fixing timbers were in vogue, but they all used the same principle: the wood had to be placed to oppose the direction in which there was the chief pressure or threat. Timbering, therefore, became the key to the new technology of underground mining, and by the end of 1860, according to the *Mining and Scientific Press* of November 30, 1860, there were no less than 400 saw mills in California worked by both water wheels and steam.

Cornish shafts were invariably rectangular, usually measuring ten feet by eight feet, and this tended to become standard practice in the Western United States. The principles of shaft sinking remained intrinsically the same over the years, but the methods changed. Sinking in rock involved drilling by hand, using a *single-jack* or *double-jack*, blasting, removing the broken rock, securing the *collar* of the shaft and timbering as the miners went down.

Sinking in soft ground, however, was another matter. One of the earliest methods involved sinking a wooden casing around the shaft area to exclude ground water and unconsolidated material. Another was to sling a pump in the shaft and to lower it from time to time as the sinking continued, a water wheel being used to make water expel water. With the passing of time came new methods such as wood-piles, steel-piles and runners, reinforced concrete caissons, and pneumatic caissons. In the 1880's, the freezing method was introduced from Germany. In this method of mine development the wet ground was artificially frozen and then blasted as if it were solid rock.

After blasting and the erection of doors or platforms to prevent rock from falling on the men below, the actual timbering of the shaft was undertaken. The method used sets of local timber (sawed redwoods in California) and working from the surface downwards as the sinking continued. The sets were secured horizontally, either close together in heavy ground (known as *cribbing)* or at certain distances from each other (called *open sets*). The latter were kept vertically apart by posts or *studdles* at their corners. Between the sets the ground was covered by *lagging* commonly three inches by six inches in section, placed upright and secured tightly against the timbers by wedges driven between the ground and the lagging. The sizes of the timbers forming the sets were selected according to the size of the shaft and the nature of the ground, which also controlled the distance between the sets. The posts or studdles had squared ends and were secured with nails.

When sufficient ground had been excavated to place a new set, the end timbers were first lowered down and put approximately in place by handing them from the last set above. Round iron rods with nuts and washers at one end and a hook at the other were passed through holes and secured by nuts and washers in the last set above. Similar rods were passed through the new end pieces and hooked to the rods from above. The long sides of the framework were lowered into place and studdles secured in the four corners. The iron rods were then secured in place and the new set was firmly held by the one above.

Adequate timbering was also the key to the next operation, that of *drifting*, the driving of horizontal workings from the shaft along or parallel to the length of the vein or lode. The *drifts* were where the real business of the mine took place. They were the working openings, usually intersected by *cross-cuts* or short lateral openings to connect the major workings. The drifts were blasted out and the muck carted away to a shaft in order to provide access to the excavation of a pocket of ore, called a *stope*. There, two generally accepted methods of extracting the ore were used. In *underhand stoping*, the ore would be approached from above, drilling downward and shooting upwards, while in *overhand stoping*, the ore would be approached from below, drilling upwards and shooting downwards.

For timbering the drifts and cross-cuts, the beams used usually measured eight inches by eight inches and were six feet long, the cap being shallowly mortised towards each end to catch the heads of the end supports or posts. The latter were pushed into place and the cap then placed on. The sets were spaced about five feet from center to center with lagging installed between them and the rock to box in the opening.

In stoping, the main problem was that of supporting the roof or *back*, and this was often overcome by leaving pillars of ore or country rock at frequent intervals wherever practicable. But generally wood had to be used for temporary support, and was preferred, since it gave ample warning of increasing ground pressures by audible cracking. The woods most liked were the long-grained timbers such as aspen, oak, fir, spruce, and chestnut. The greatest revolution in mine timbering came in 1860 when Philip Diedersheimer at the Ophir Mine on the Comstock devised his pre-fabricated *square-sets*. In a short time these became a universal method of timbering, for *square-sets* could be adapted to almost every kind of irregular orebody.

3. Mineral Development Characteristics

Most of the Western mine development in the period prior to 1872 was undertaken by small companies or partnerships financed by regional capital. In a few instances, financial interests from the Eastern United States and Europe became involved in mine development in the West, but such participation was usually limited until working mines had been fairly well developed by their local owners and operators. In addition there were many small mines in operation that had been developed solely by their individual owners. The number of multi-property minerals companies was practically nil. Mining companies were generally formed to develop and operate one mine, and their fortunes often rose and fell on a single orebody.

The development of mineral properties prior to 1872 was limited in the West to relatively few commodities. Gold, of course, dominated the industry while silver, mercury, lead, and limestone were about the only others of any interest at all. The area's limestone deposits were developed on a strictly local basis as needed for immediate construction requirements. In most cases limestone was removed as needed, and for all practical purposes, the development and mining phases coincided. In certain respects the same was true of the surface deposits of lead carbonate ores then in use. Only gold placer deposits normally entailed any method of development distinct from the other minerals. The development of gold, silver, and mercury in hard-rock deposits was basically alike for each of the three minerals.

The time required for mineral deposit development prior to 1872 was minimal. The occasions were rare indeed when more than a few months would be spent in sinking shafts and developing underground workings before removing the first ton of ore. In many cases, development workings would be driven in the ore itself so that development and production actually coincided.

Development costs in the 1800's, while small by today's standards, were still substantial in terms of the personal income patterns and purchasing power of the time. Nevertheless, relative to the value of the ore mined and compared to operating costs, mine development costs prior to 1872 were relatively slight.

The amount of land necessary for mine development in the 1800's was also relatively small, compared to today's requirements. The established reserves felt necessary for initial mine development were comparatively meager and the very nature of the vein and placer deposits then being worked as well as the existing technologies precluded the need for large areas. For underground deposits virtually all that was needed was space for the mine workings themselves, the immediate surface plant (a hoist and perhaps a shop), and living quarters for the miners. Under the apex principle, it was not even necessary to have as much land area as that covered by the deposit being developed. The number of small (less than 20 acres) fractional mining claims developed in the 1800's was substantial.

Most of the minerals utilized in the 1800's in the Western United States had already established markets. In fact, if there were not usually an established market for a particular commodity, it was neither sought nor developed. The very absence of markets or ways to get to them was what delayed the development of many of the West's mineral resources. The fact that there were established markets only for gold, silver, and mercury made them the first minerals to be developed.

Figure 21 - Some metalic mineral deposits mined in the late 1800's were developed in ore almost from the surface, and little or no pre-production development was required. High-grading, *the practice of excavating only rock of high value, was common, and involved a minimum of development work.*

C. CHANGES IN MINERAL DEPOSIT DEVELOPMENT TO 1947

1. The Pattern of Large Mine Development

Gradually the markets for both metals and industrial minerals from deposits in the Western United States grew, and as they did, technology and the nature of the deposits mined also changed. Undoubtedly the most significant event to affect mineral deposit development in the West between 1872 and 1947 was the initiation of successful large-scale mining and beneficiation operations at Bingham Canyon, Utah, in the first decade of the 1900's. This event ushered in the day of large-scale preproduction expense and made mine development a distinct phase in the utilization of mineral resources.

The development of the deposit at Bingham for large-scale mining was in many ways typical of the development of other such deposits in the early 1900's. Prior to that time, the development of many of the richer copper deposits had in reality involved mining at increasing depths, with each successive mining venture in effect further developing the orebody. With Bingham, however, development became a conscious effort to establish a system and surface plant for large-scale production.

Utah Copper owes its being to the faith that Daniel C. Jackling had in it. After several deals for development of the mine fell through, Jackling at last secured an option from the deposit's owner and went for financial backing to the Penrose Brothers, then very active and successful in Western mining. After more testing of the deposit, the Utah Copper Company was organized in 1903. Only $250,000 was available at the start. Several million dollars still had to be found. The Guggenheim Exploration Company and Hayden, Stone and Company underwrote several bond and stock issues, mainly to build the Magma Mill at Garfield. Capitalization was then $7,500,000. After a further increase in capitalization, production from the open pit started in 1907.[46]

The first successor to Utah Copper was at Ely, in Eastern Nevada. Jackling was involved there also, because the Nevada Consolidated Copper Company, organized in 1904, was controlled by the Utah Copper Company. First production from the open pit porphyry copper deposit at Ruth, near Ely, was recorded in 1908.[47]

In 1911 the underground block-caving of disseminated ore began at Ray, 70 miles southeast of Phoenix, Arizona. The Ray Consolidated Copper Company was organized by D. C. Jackling and associates, Seeley Mudd and Phillip Wiseman, after several abortive attempts at production at intervals since 1880. Transition from underground to open pit mining came only after 1947.[48] The beginning of large-scale underground mining at Ray marked the beginning of the need for extensive initial development (other than shaft sinking) in underground mining in the West. With this method, the ore produced from development workings was too low in quality and quantity to be considered significant as production material. Furthermore, the caving system required much more extensive underground preparation than had earlier mines in veins or massive replacement deposits.

In the same year (1911), underground mining by block-caving began at the Miami Copper Company deposit at Miami, Arizona, 16 miles northeast of Ray. Until the late 1920's the grade of ore averaged about two percent copper, higher than most of the porphyry copper ore.[49] In 1911 production started also at Santa Rita (Chino) in Southwest New Mexico where small-scale mining of oxidized copper ores and native copper had been going on sporadically for over 100 years.[50]

The Inspiration Consolidated Copper Company was incorporated in 1911, after several sporadic and mostly unsuccessful attempts at mining the copper ore on the property it had inherited in the Globe-Miami district of Arizona. Production started in 1915 at Inspiration with an 18,000 tons per day concentrator, the first to employ an all-flotation process. The other operators soon followed suit. From 1915 to 1947, block-caving was used. From 1948 to 1961, a combination of block-caving and open pit mining was employed, and from 1961 to date, open pit mining has been used exclusively.[51]

2. Development Scale and Costs

In the period from 1912 to 1915, Inspiration developed its mine for block-caving and erected the necessary surface plant, including a concentrator that was regarded as the last word at the time. The projected capacity of the operation was 60,000 tons of copper per year. The company did not build its own smelter; but the cost of the nearby international smelter, that was to treat both Inspiration and Miami concentrates on a custom basis, was about $3,000,000. That would make a total capital investment of $19 million. Forty years later, the San Manuel Copper Corporation invested nearly $100 million for facilities needed to produce 70,000 tons (16 percent more) of copper per year by almost identical operations involving underground block-caving, concentrating, and smelting. The reasons for this rather startling difference are numerous, but a few of them are of prime importance in the changes that have taken place in mine development since the 1800's.

First, Inspiration planned to mill 15,000 tons of ore per day compared with 30,000 for San Manuel. The reason is that Inspiration ore averaged 1.6 percent copper against 0.8 percent for San Manuel. This higher rate of production in itself involved more extensive mine development in the 1950's with more underground transportation facilities, larger hoisting works and, of course, a mill-concentrator (though *not* a smelter) with twice the capacity of Inspiration's development in 1915. Second, the underground and surface machinery installed by Inspiration were less efficient, and less expensive, than that installed at San Manuel in the 1950's.

A third factor, of course, is general inflation and consequent deterioration in the purchasing power of the dollar that has taken place since 1915. The identical hoist that Inspiration bought in 1914, if it could have been duplicated in 1954 (which, of course, was neither desirable nor possible), would have cost at least twice as much. Wage scales for construction workers were at least three times as high in 1954 as they were in 1914. A fourth item that kept the earlier costs down was that Inspiration was obliged to build neither 25 miles of railroad nor a $10 million town to house and otherwise provide a comfortable environment for its employees as was San Manuel.

Over the period from the late 1800's to 1947, the increasing capital requirements of mineral deposit development led to the formation of larger and larger mining firms. As a result, by 1947 most of the major nonferrous metals mines in the West were owned by a handful of large companies. The individual property companies had been largely combined into national minerals firms, although a few single-property producers still existed, particularly in the higher unit value operations such as silver and mercury.

After the rash of development related to the porphyry coppers in the first two decades of the century, however, the extent of new mine development in the West declined, coming almost to a halt in the 1930's. World War II provided an impetus to new mine development, but aside from the conversion of the Morenci, Arizona, deposit to a large open pit operation, the development of new metallic mineral properties remained sparse. Only after the end of World War II did new mine development again come to the fore in the Western United States.

D. CHANGES IN MINERAL DEVELOPMENT SINCE 1947

1. The Development Process

Although mineral deposits may be found, mines are made. This was true in the last century and it has remained true in this one. Since 1947 the truth of the distinction between a mineral deposit and a mine has become even more apparent as the making of mines has required a greater utilization of available technology and more time, more money, more space, and more minerals than ever before.

Although mineral development since the end of World War II has tended to involve more of everything concerned, the basic process has remained the same. Development still involves sufficient and appropriate excavation to expose the orebody and the installation of the proper surface and underground facilities to facilitate the removal and processing of the ore. Development for surface mining still requires the stripping of overburden, and the development of an underground mine still requires (usually) the sinking of a shaft and the driving of horizontal openings under, in, or around the ore.

The equipment involved in mine development has changed since 1947. The surface plant facilities are normally larger and more complex. The overburden removal equipment is larger and more expensive. Newer shaft-sinking methods have increased the speed of underground development, and the necessary size of underground openings has grown. These changes in the scale and capabilities of development equipment have all had their effects on the various dimensions of the mine development process—time, money, and space.

2. Development Time Requirements

An orderly development program permitting the best mineral conservation and the greatest economic benefit takes time. Of course, there are upper as well as lower limits on the time involved, but within a rather wide range there are a number of time-dependent conditions involved in bringing a modern mine from the first recognition of the existence of an orebody to the full-scale production of a mineral commodity.

Security of tenure and freedom for changes in plans are essential to proper mine development. If a long-term title to a mineral deposit is not available, the result is likely to be a brief "high-grading" operation. There are innumerable examples of orebodies once mined to their apparent high-grade limit and abandoned- only to be reopened under longer-term conditions years later for a greater overall profit.

Any short-term agreement, be it option or lease, may cause abandonment of a project just as the information for an orderly development program is beginning to come to light. This came very close to happening at Bingham Canyon, Utah, when, in 1895, Joseph DeLamar secured a six-month option agreement on an attractive-looking prospect.[52] His sampling and concentration tests during this time, however, were not immediately encouraging. DeLamar secured a second six months option in 1898 and obtained satisfactory indications. He was not, however, able to obtain an extension of time in which to verify his findings, and he did not exercise his option on the property. In 1899, he was persuaded to re-enter the scene with a new one-year option agreement. Again the results of tests were inconclusive and the option was not exercised. It was not until 1903 that a mining pioneer, D.C. Jackling, was able to obtain a suitable arrangement involving a six months option agreement with provisions for an additional 12 months extension. The masterful job of evaluation, development, and engineering which followed gave rise to the Utah Copper enterprise in 1907 and is now a classic in American mining history. It should be noted, however, that DeLamar had just as much elapsed time in examination as did Jackling.

Changes in plans as a result of unforeseen circumstances are of importance in most mine development histories. Orebodies and their surroundings are full of surprises, and effective management must be able to "roll with the punch," and to make new decisions based on new information. Experience in developing the Palo Verde copper mine in Arizona serves as an illustration of the period since 1947.[53] In February 1956, an exploration drill hole penetrated 335 feet of low-grade disseminated ore at the property. Additional drilling during the next few years indicated a large orebody suited to open pit mining but requiring financing of $40 million or more. In the course of the drilling program, a zone of higher-grade ore was encountered which, however, was too deep for extraction by any open pit then feasible. A decision was made in early 1959, therefore, to sink the 1,030-foot Palo Verde shaft to the higher-grade zone and to mine a portion of the orebody by underground methods as an intermediate step in planning for a larger open pit mine. The sinking was delayed by a large inflow of water at a depth of 960 feet, and it took nearly a year to control the inflow and dewater the shaft. Production from the Palo Verde Mine began in November 1961. Under an agreement specifying in advance the exact type, amount, and location of work to be done, such a development program would have been especially complicated and probably not carried out.

A great many factors are involved in the time needed for the development of a mine. Some of these, including primarily the physical conditions inherent in the mineral deposit, are essentially static. The lateral dimensions, depth, and continuity of the mineral deposit are no different today than they were a century ago. (This is not necessarily true of the orebody, however.) The remaining conditions are dynamic and involve the changing aspects of technology and economics. They provide the pattern within which many older small mines and non-commercial prospects have become today's major mines, and conversely within which many of yesteryears' mining districts have been turned into ghost camps even though considerable mineralization was still in place.

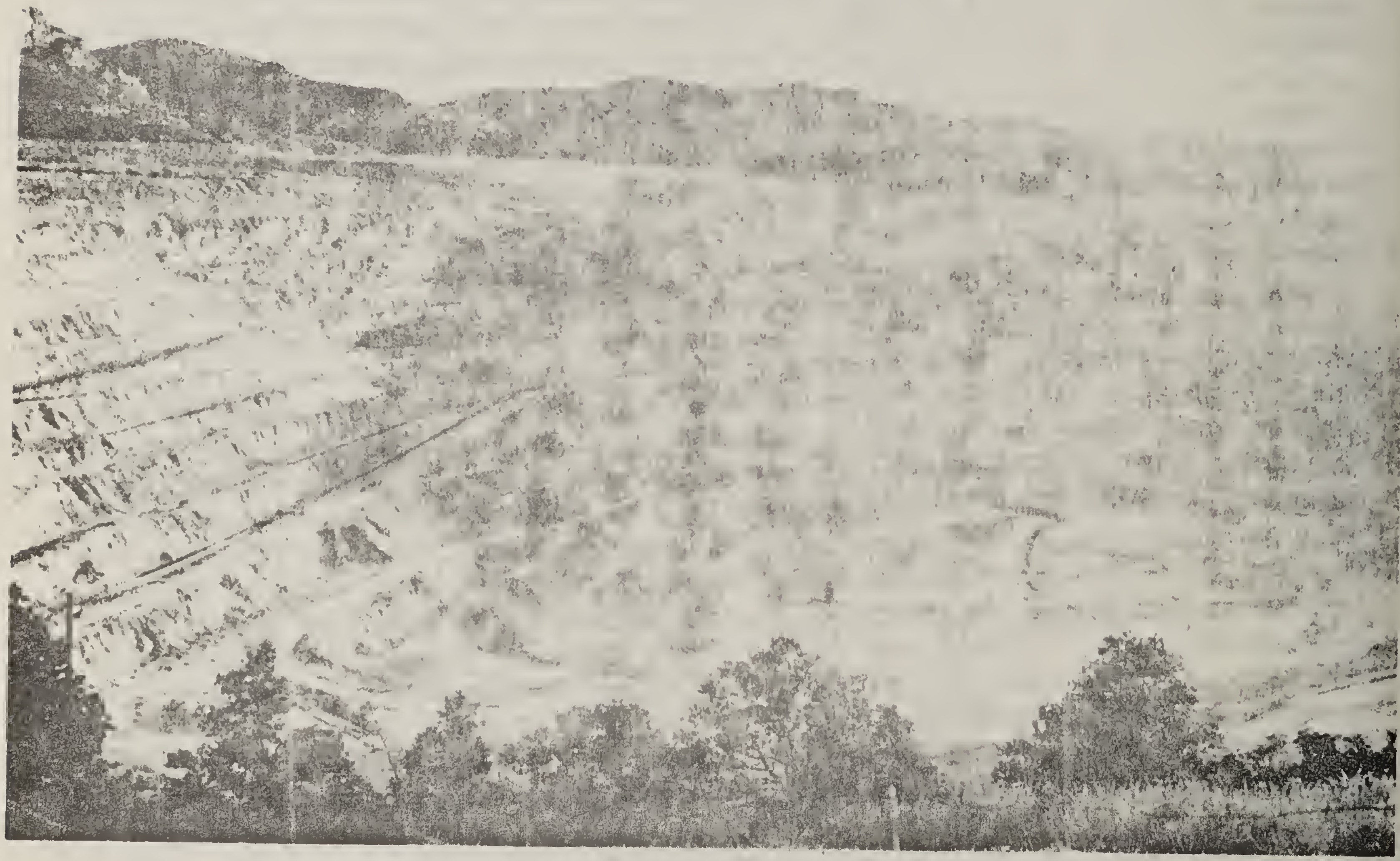


Fig. 22 - The Chino Mine at Santa Rita, New Mexico. The small-scale mining of high-grade surface deposits of native copper and copper oxides required little in the way of mine development prior to 1911 when large-scale mining of the larger disseminated copper porphyry was begun. The initiation of large-scale mining started the need for extensive pre-production development work.

Mining conditions have important bearings on the length of the mine development period, and many of them may act on different facets of the development process. The overall development time involves a critical path determined by the most time-consuming sequential activities. An orebody may be outlined while mill tests are being made. The mine may be designed, haul roads surveyed, and markets developed, all while capital is obtained. The construction of a mill and smelter may go on at the same time as stripping, townsite construction, reservoir work, and purchase of mining equipment. Figure 23 illustrates a hypothetical four-year pre-production program schedule that is typical of many mine development programs that have been followed since 1947.

In some cases, such as at the Gunnar Beaverlodge uranium mine in Saskatchewan, Canada, the development of a small open pit and a larger underground mine progressed simultaneously so that early pit production could furnish revenue while underground development was in progress. A combined open pit-underground development procedure was used much earlier at Bingham Canyon, Utah, but with underground mining furnishing ore while the longer-term stripping of overburden was performed.

The pre-production interval (considered as the time between recognition of a significant potential orebody and the beginning of significant ore production) may even now in special cases take only a few months or even days. Very small orebodies close to an assured market, near the surface, and requiring only such equipment as a compressor, drill, loader, and a single truck are of this type. Many of the uranium deposits mined during the 1950's were partially exposed at the surface and were so limited in size that they were brought into production almost as soon as discovered. With a small orebody, such activities as preliminary drilling, engineering, and preparation are kept to a minimum.

Mines capable of supporting more than a few miners and production of more than about 50 tons per day, however, are not so quickly developed. Most mines today may be categorized into four major groups. The first normally requires two years or less of pre-production effort (exclusive of exploration). These are characterized by near-optimum physical conditions, an ore that is not complex and has a high unit value. Technologic conditions are also favorable in that conventional mining and processing methods are applicable, and there is no need for new large-scale transportation facilities. Economic conditions are such that a ready market is assured and only short-term financing is necessary.

The second group involves from two to five years of pre-production time. A majority of the new mines fall in this group. Physical, technologic, and economic conditions may be said to be "average." A third class entails from five to seven years of pre-production activity. Many of the large-scale mines with low unit value ore and complex processing or marketing problems that have been developed since 1947 are in this category. The fourth and final group requires seven years or more of pre-production effort. These mines are characterized by difficult physical conditions, large technological problems, and complex economic problems.

The pre-production intervals do not include the time spent on reconnaissance and detailed target investigation prior to the recognition of a significant potential orebody. At the Pea Ridge iron mine in Missouri, for example, the seven year pre-production interval which began in 1957 was preceded by ten years of exploration and by a still earlier period of five or more years during which the district was known to have iron ore of possible interest. The Bagdad and Silver Bell copper mines in Arizona were brought into production in two years and six years, respectively, but the existence of both mineral deposits had been known for more than 60 years.

Many presently operating mines cannot be assigned a definite pre-production interval. Some are older mines with a long history of production that has expanded from a few tons per day initially to several thousand tons per day at present, involving growth that has been almost continuous with the addition of facilities being made during much of the mine's life. Some pre-production intervals have been interrupted by wartime shortages of material and labor. In other cases there have been stages of inactivity, with each productive stage

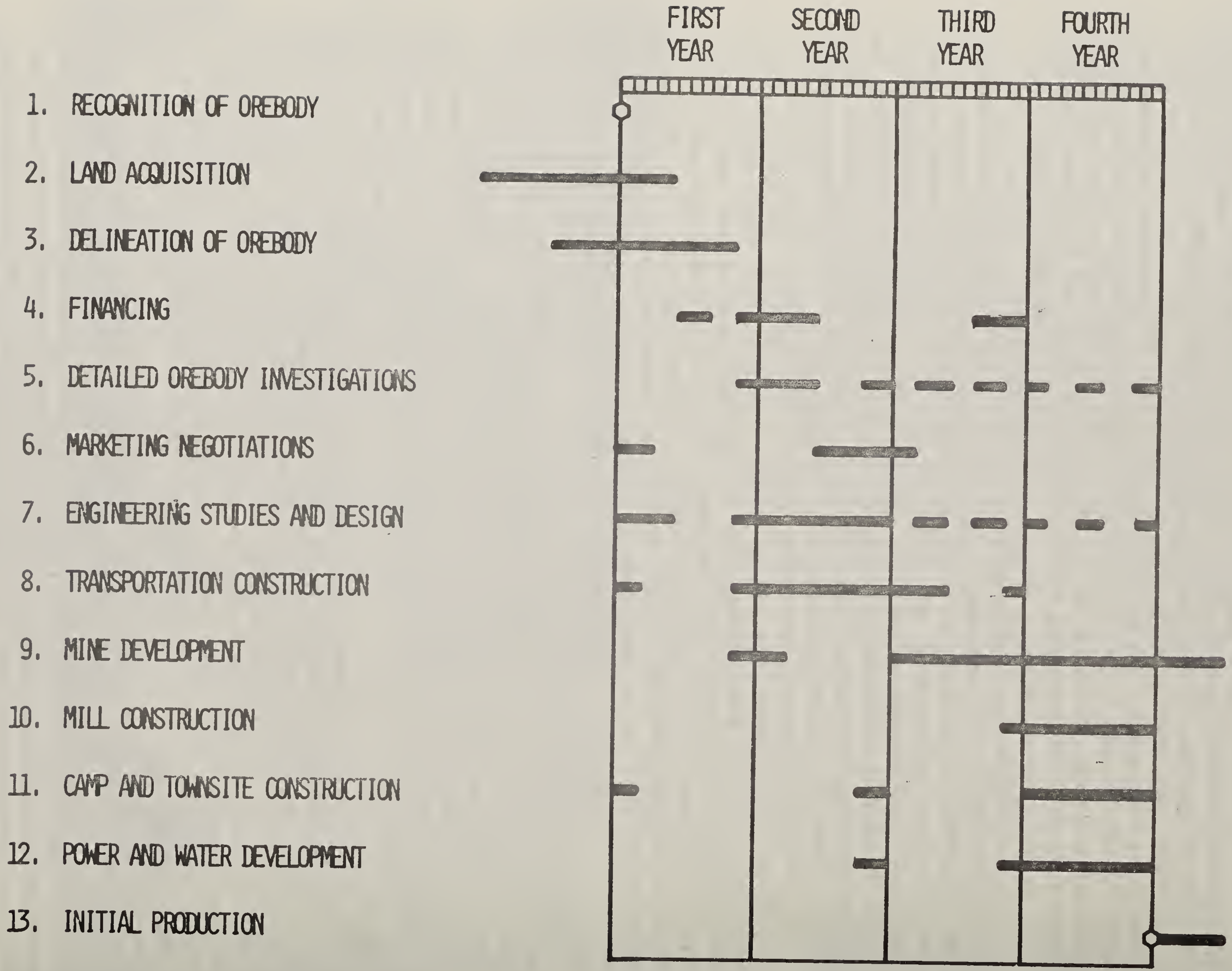


Fig. 23 - Typical scheduling plan for a four year mine development program. Some functions are carried on intermittently through the period while others must be

involving the rehabilitation of previous workings. Such is the typical history of the Bluebell lead-zinc mine in British Columbia,[54] where underground development began in 1886. Operation periods were from 1894-1896, 1908-1910, 1912-1920, and 1920-1927. In 1947, a new drilling and underground development program began. Significant production was resumed again in 1952. In this instance, the pre-production interval might be taken as eight years (before 1894), five years (before 1952), or even some assigned portion of 66 years.

Mines with two years or less pre-production time include the examples shown in Table 16. Some were brought into production as a result of immediate national interest. Many tungsten, manganese, and vanadium mines which began production during wartime were developed with government participation and with the effective by-passing of many normal peacetime economic delays.

During the scramble for uranium in the 1950's, many mines of all sizes were brought into production within a very short time. Government bonuses, loans, purchasing stations, and guarantees made economic conditions exceptionally favorable. Physical conditions were also generally favorable in that a majority of the deposits were small and shallow. In the Uravan mineral belt in Colorado, uranium orebodies range from 50 tons to more than 100,000 tons. The average orebody contains from 5,000 tons to 15,000 tons, and depths range from 50 feet to 750 feet. Such shallow deposits have normally required a development interval of only from three to six months for underground mining. Deeper deposits and generally larger deposits have required from one to two years for the proper shaft sinking and other development work. A common practice in the uranium rush was to start an entry as soon as enough ore was outlined to recover the entry costs. Additional ore was then located after initial production had begun.

Mines with short pre-production intervals are characterized by high unit value ore located in known and accessible areas. The gold of the 1850's and the uranium of the 1950's were similar in this (and many other) respects. Initial production capacities are on the order of a few hundred tons per day or less. There are some outstanding exceptions, however, such as the Kidd Creek mine near Timmins, Ontario, where the development of an open pit mine with a mill and a 16-mile rail spur allowed production to begin at 6,000 tons per day during 1966, about two years after the recognition of a definite orebody. The five-year exploration program which preceded the discovery of the Timmins orebody, however, involved thousands of square miles of geologic reconnaissance plus the drilling of 65 other geophysical anomalies.

Most of the new mines that have been developed since 1947 are included in the group with two to five years pre-production. Examples are given in Table 17. Conditions for these mines may be described as "average." It is, however, well understood that each mine is unique and that there really is even less chance of finding an "average" mine as there is of finding an "average" man. Physical and technologic obstacles have sometimes been difficult in this group. The Consolidated Discovery Yellowknife mine's four years pre-production period included the shattering loss of an entire beneficiation plant in the sinking of a barge in Great Slave Lake. The 4.5 year pre-production interval at Bingham Canyon, Utah, included technologic and economic accomplishments of immense proportion. Perhaps the "average" connotation should be restated as an averaging of difficult conditions plus extremely competent and energetic personnel!

An idea of the factors affecting the development interval for "average" mines may be obtained from examining a period in the history of gold mining. The United States gold price was raised from $20.67 per ounce to $35.00 per ounce in January 1934. The Canadian gold price had begun rising three years earlier in anticipation of the United States action, but the real economic impetus for new gold mining came in 1934. Of 55 new gold mines opened in Ontario during the period between 1934 and 1942, eight came into production within two years, 41 came into production between two and five years, and six came into production between five and seven years.[55] The representation is not perfect in that wartime shortages began to interfere in 1940. Still, the illustration shows a strong modal average of two to five years for development.

Table 16

SELECTED MINES WITH TWO YEARS OR LESS DEVELOPMENT TIME, THE UNITED STATES AND CANADA

	Initial Production				
Property	Commodity	Amount (tons/day)	Year	Type of Mine	Develo Tin (yea
Boriana, Arizona	Tungsten	50	1931	Underground	1
Madsen Red Lake, Ontario	Gold	300	1938	Underground	1
Williams, Arizona	Tungsten	75	1940	Underground	1
Walton, Nova Scotia	Barite	400	1941	Open Pit	1
Castle Dome, Arizona	Copper	10,000	1943	Open Pit	2
Eagle Mountain, California	Iron	8,000	1948	Open Pit	2
Weedon, Quebec	Copper	250	1952	Underground	2
Mineral Hill, Arizona	Copper	350	1953	Underground	1
Yerington, Nevada	Copper	12,000	1953	Open Pit	2
Daisy, Arizona	Copper	100	1954	Underground	1
Rio de Oro, New Mexico	Uranium	60	1956	Underground	1
Radon, Utah	Uranium	250	1956	Underground	1.
Denison, Ontario	Uranium	2,000	1956	Underground	1
Brynnor, British Columbia	Iron	3,000	1962	Open Pit	2
Lac Dufault, Quebec	Cu-Zn	1,300	1964	Underground	2
Kidd Creek, Ontario	Zn-Cu-Ag	6,000	1966	Open Pit	2

Sources of data: Various

In the group of mines with five to seven years pre-production time, there are examples of operations with more complex geologic conditions and with more difficult engineering problems. A few of these mines are listed in Table 18. Many of these, including some iron, bauxite, and salt mines, are characterized by relatively low unit value commodities and consequently by a need for very large scale haulage systems. In many instances, it has been necessary to include the conduct of extensive beneficiation and mining tests, railroad building, and the construction of supporting facilities in the development stage.

At the Atlantic City, Wyoming, iron mine, for example, a detailed diamond drilling program was begun in the summer of 1955 at the time of deposit recognition. Preliminary engineering work started in 1956. Underground work for obtaining bulk samples to be used in further concentration and agglomeration tests and more diamond drilling had to be done prior to breaking ground in 1960 for a taconite processing and agglomerating plant. Construction of a 76-mile rail spur and stripping for the open pit mine took place in 1961 and 1962. Shipment of the first carloads of agglomerate in August, 1962, marked the successful completion of seven busy years of mine development that included stripping, plant construction, road, railway, and reservoir building, and the installation of power facilities.

At the Wedge copper-lead-zinc mine in New Brunswick, Canada, recognition of a potential orebody in 1956 began a six-year mine creation program.[56] In order to delineate the orebody, a two-year project involving 20,000 feet of diamond drilling followed. Since metallurgical difficulties were anticipated, it was necessary to sink a 1,150-foot deep shaft in order to obtain adequate bulk samples for evaluation and testing. This part of the program involved road building, camp construction, plant construction, and the installation of power facilities. Lateral development work underground and additional diamond drilling followed. The decision to enter full-scale production was made early in 1961 and production began in January 1962, six years after recognition of the mineral deposit as a potential orebody.

A specific economic factor becomes involved in the development of mines over more than seven years. This is the time value of investment money. Private investors ordinarily are not willing to wait for more than six to eight years for a mining property to begin paying for the initial investment. Term loans from banks in the form of first mortgage bonds are obtainable for a maximum of three to five years, and only in exceptionally attractive cases, for a maximum of eight to ten years.[57] Repayment of credits to the Export-Import Bank of Washington, an organization especially designed for large-scale global economic development, commonly takes from eight to ten years.[58] Long-term institutional bonds or notes with a maturity period of ten to 25 years are available only to mines well past the initial development stage that have achieved this status of an operation comparable to a low-risk manufacturing enterprise.

Among the mines that have required more than seven years in pre-production time are some of the very large, complex, or deep operations in which the overall financial risk has been relatively low and the return on investment so attractive that the preliminary financing has been possible in spite of a long pre-production delay. Financing for this type of venture has often been completed in stages, with re-financing an important factor and with the largest outlay taking place during the final development years when the uncertainty has been the least. Financing sometimes has been assisted by early high-grade shipments during the long pre-production period.

An example of a long-term pre-production period is the Schefferville iron operation in Labrador and Quebec where production began in 1954, 12 years after the economic importance of the site was recognized and nine years after the actual development engineering studies began. Financing for full-scale construction was accomplished in 1950. The pre-1950 work included drilling, test pitting, evaluation, and engineering planning. From 1950 until 1954, there was a remarkable program of railway building for a distance of 357 miles, mine development, construction of a port, plant, and townsite facilities, and installation of a hydroelectric power plant. The result was monumental, a new mining complex capable of producing 20 million tons of ore per year in wild and rugged country. But it took time and money.

Table 17

SELECTED MINES WITH TWO TO FIVE YEARS OF DEVELOPMENT, UNITED STATES AND CANADA

		Initial Production			
Property	Commodity	Amount (tons/day)	Year	Type of Mine	Developn Time (years
Pamour, Ontario	Gold	750	1936	Underground	3
Berens River, Ontario	Au-Ag	225	1939	Underground	3
Bagdad, Arizona	Copper	2,500	1944	Underground	3
Consolidated Discovery Yellowknife Northwest Territories	Gold	100	1950	Underground	4
Quebec, Quebec	Copper	450	1954	Underground	4
Indian Creek, Missouri	Lead	2,500	1954	Underground	4
Gunnar Beaverlodge, Saskatchewan	Uranium	1,250	1955	Open Pit	3
Campbell Chibougamau, Quebec	Copper	1,700	1955	Underground	4
National, Nova Scotia	Gypsum	6,000	1955	Open Pit	4
Esperanza, Arizona	Copper	12,000	1959	Open Pit	4
Sunro, British Columbia	Copper	1,500	1962	Underground	2.5
Coalinga, California	Asbestos	2,500	1962	Open Pit	3
Zeballos, British Columbia	Iron	3,200	1962	Open Pit	3
Locust Cove, Virginia	Gypsum	1,000	1964	Underground	4
Brookfield, Nova Scotia	Limestone	1,800	1965	Open Pit	4
Carlin, Nevada	Gold	2,000	1965	Open Pit	3
Endako, British Columbia	Molybdenum	10,000	1965	Open Pit	2.5
Fletcher, Missouri	Lead	5,000	1966	Underground	3

Sources of data: Various

In the Western United States, examples of large mines with long pre-production histories determined by economic conditions include the Clay copper pit at Morenci, Arizona, and the San Manuel copper mine, also in Arizona. The Clay pit began production in 1942 at a capacity of 25,000 tons of ore per day. Recognition of the large low-grade orebody had been firm, however, since about 1929. Extensive diamond drilling, mine planning, and mill testing were carried out during the depression years of the 1930's. Stripping and plant construction did not become economically possible until 1937. As a result, the pre-production interval amounted to about 13 years. At San Manuel, the potential of the orebody was recognized in 1944. Financing on the order of 100 million dollars was, however, not obtained until 1952, and then it was provided by the Reconstruction Finance Corporation. The subsequent three and one-half year intensive development program with a new mine, mill, smelter, railroad, and townsite led to the opening of one of the world's largest block-caving operations at a daily production rate of 33,000 tons of ore.

In some instances, a long pre-production interval has been carefully set so that a new mine can replace an older one as the latter is depleted. In established industrial areas, a smooth transition can thus be made to a new source of ore. Such was the case of the Copper Cities mine in Arizona where, after an 11 year pre-production interval, open pit production began in 1954. The ore was processed by a 10,000 ton per day concentrator that had been moved from the recently depleted Castle Dome mine of the same company.

Long pre-production intervals are not entirely confined to large-scale enterprises. In a relatively few small mining operations there have been more than seven years of development time because the early efforts were borne by a small group of individuals with limited financing. The Arntfield gold mine, Quebec, became a 125 tons per day producer in 1935 after a 12 year pre-production interval during which a small crew worked on the property every single day.

Some mines with more than seven years of pre-production time were actually planned for earlier operation, but they were beset by unforeseen difficulties. The first shaft into the potash beds at Esterhazy, Saskatchewan, required two and one-half years just to seal off a troublesome water-bearing zone. This was a large factor in stretching the mine's pre-production time to seven years. A second shaft at the same mine penetrated and sealed off the same zone in four months.

The time needed for rehabilitation of a flooded and collapsed shaft or for the solution of an unsuspected milling or marketing problem has often been complicated by the need for additional financing. Metallurgical problems have been especially difficult to foresee until enough ore has been made available for large-scale mill testing. Metallurgical problems were factors in the long pre-production interval at the Brunswick (12 years of development) and Heath Steel (eight years of development) mines in New Brunswick, Canada.

The general pre-production time interval, like the dynamic conditions which control it, might be expected to have changed from decade to decade. Actually, many of the changing conditions have operated in opposing directions so that the interval has remained about the same, at least since the early 1900's. In recent years, the techniques of orebody delineation by drilling have been speeded-up. Aircraft transportation of men and equipment to exploration and development sites has supplanted the earlier time-consuming methods. Earth moving, shaft sinking, and plant construction have all reached new peaks of speed and efficiency. These features, which have accelerated mine development, however, have been offset by the very nature of the orebodies now being brought into production. Orebodies have become more complex in every respect. Rather than being accessible, the remaining orebodies are likely to be deep and hidden. The unit-value of the ore may be so low as to have been in the waste category a few years ago. The profitable operation of low-grade mines requires extensive preparation for bulk materials handling and complex processing. At a new copper mine in Arizona, a fleet of 29 trucks worked around the clock for almost two years to strip 45 million tons of overburden from an orebody to a depth of 200 feet. At another Arizona mine, it has taken three and one-half years to strip 165 million tons of overburden to a depth of 460 feet and a length and breadth of one-half mile.

Table 18

SELECTED MINES WITH FIVE TO SEVEN YEARS OF DEVELOPMENT, UNITED STATES AND CANADA

		Initial Production			
Property	**Commodity**	**Amount (tons/day)**	**Year**	**Type of Mine**	**Developme Time (years)**
Eldorado Beaverlodge, Saskatchewan	Uranium	500	1953	Underground	5
Lynn Lake, Manitoba	Nickel	2,000	1954	Underground	7
Silver Bell, Arizona	Copper	7,500	1954	Open Pit	6
Lavender, Arizona	Copper	12,000	1954	Open Pit	6
Gaspe, Quebec	Copper	1,500	1955	Underground	7
H. Young, Tennessee	Zinc	2,500	1955	Underground	6
Gunnar Beaverlodge, Saskatchewan	Uranium	1,650	1957	Underground	5
Pima, Arizona	Copper	3,000	1957	Open Pit	5
Viburnum, Missouri	Lead	4,000	1960	Underground	5
Thompson, Manitoba	Nickel	6,000	1961	Underground	5
Quebec Cartier, Quebec	Iron	10,000	1961	Open Pit	5
Wedge, New Brunswick	Cu-Zn-Pb	750	1962	Underground	6
Pea Ridge, Missouri	Iron	12,000	1964	Underground	7
Mineral Park, Arizona	Copper	12,000	1964	Open Pit	5
Cleveland, Ohio	Salt	15,000	1965	Underground	7

Sources of data: Various

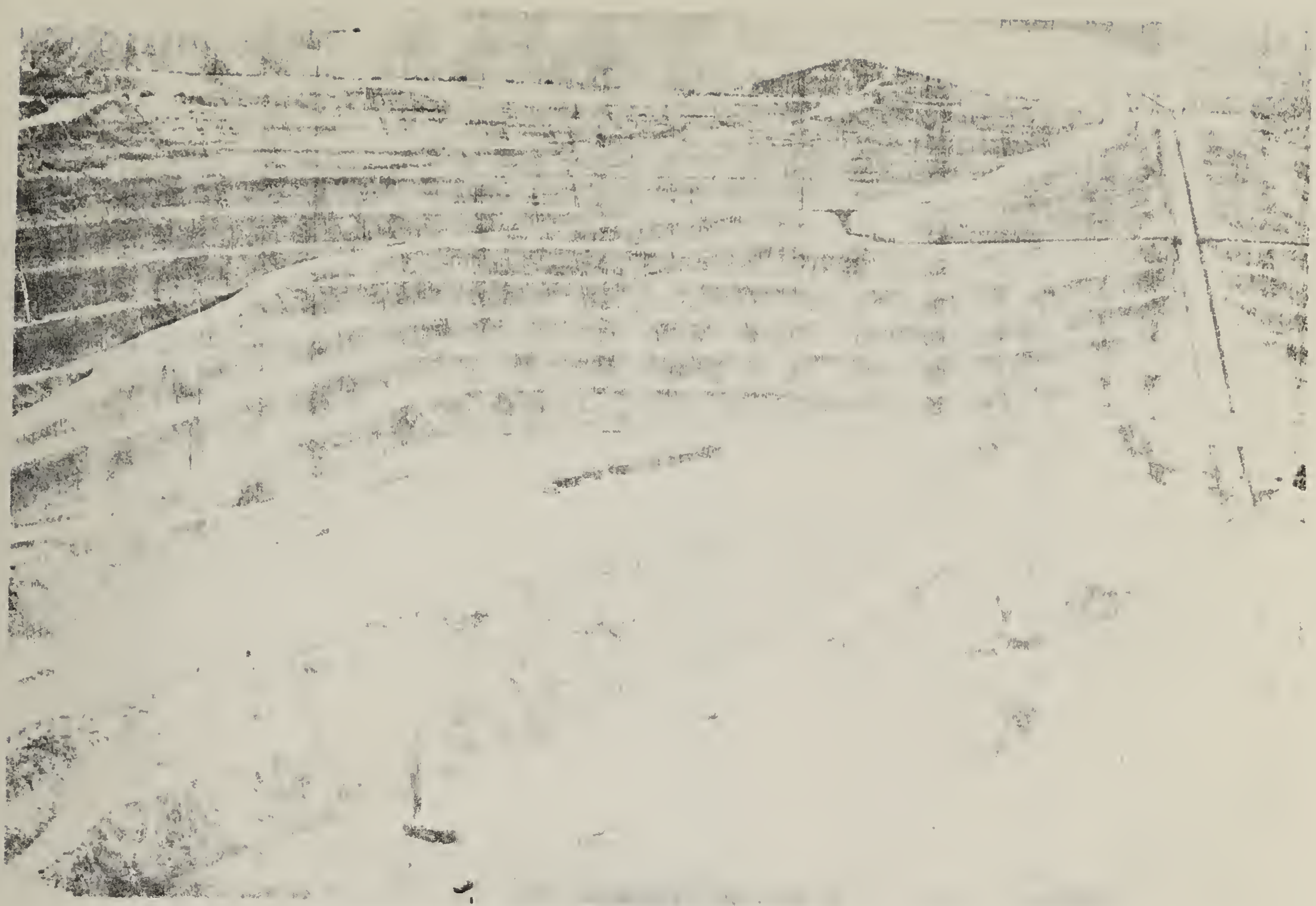


Fig. 24 - Modern mine development often requires the removal of millions of tons of overburden before even one ton of ore can be mined. This view of the Anaconda Company's stripping operation at Twin Buttes, Arizona, shows the extent of the development work required in preparing some large mineral deposits for mining. Although a portion of the top of the orebody had been uncovered, no actual mining had begun by the date of this picture (early 1969).

The conditions involved in determining the pre-production interval for any mine are so interrelated that any averaging of information must be accepted only in the broadest sense. A newly discovered orebody, large or small, with a very favorable balance of physical, technologic, and economic conditions can normally be brought into production within two years. A great many new orebodies of all sizes, however, now require from two to five years of development. Orebodies with a low unit-value or with complex conditions require as much as seven years of pre-production time. A development time of more than seven years has been experienced only at those relatively few mines where the projected return on investment has been so well established by preliminary investigations and has been so attractive that long-term financing could be obtained. Unforeseen difficulties, however, have resulted in a long pre-production interval, and unforeseen difficulties are always a possibility in mineral resource development.

3. Mine Development Costs

The growing importance of capital investment and the need for ever larger amounts of pre-production funds have been caused in large part by the more costly nature of mine development, including beneficiation and advanced processing plant construction. Some of the unit costs involved in uranium deposit development are shown in Table 20. The relatively small size and near-surface location of the nation's uranium deposits that have

Table 19

REPRESENTATIVE TIME INTERVALS INVOLVED IN MINE DEVELOPMENT IN THE UNITED STATES

1947 – 1968

Project (Ranked by Length of time)	Commodity	Development Time[a] (in months)
1	Barite	144
2	Iron	120
3	Copper	120
4	Potash	96
5	Evaporite	60[b]
6	Lead	60
7	Iron	50
8	Lead	48
9	Limestone	44
10	Lead	42
11	Copper	36
12	Clay	36
13	Molybdenum	24
14	Lead	24
15	Phosphate	24
16	Sand	24
17	Copper-Zinc	18
18	Uranium	18
19	Industrial Minerals	18
20	Gypsum	18
21	Uranium	16
22	Uranium	16
23	Gypsum	12
24	Uranium	12
25	Uranium	12
26	Uranium	12
27	Uranium	10
28	Uranium	8

[a] Time from recognition as an orebody to first significant production.

[b] Largely pilot plant testing.

Source: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

been developed to date have been responsible for keeping total uranium development costs relatively low compared to other minerals although unit development costs are similar.

Unit development costs involved in the preparation of the nation's large copper and iron deposits have been relatively low, as shown in Table 21. The enormous volume of development work required, however, in preparing these deposits for mining has kept the total investment in new copper and iron properties high. The same is true in the development of other large disseminated mineral deposits, as shown in Table 22.

Total development costs, and consequently, the initial investment required for the development of a mineral property in the United States, have varied widely in the last two decades and still are quite divergent. Most of the larger development expenditures have involved the development of large, disseminated copper and/or molybdenum deposits, as well as phosphate and iron deposits, and have ranged up into the hundreds of millions of dollars. A more representative sample of total mineral development costs for deposits other than copper porphyries is shown in Table 23.

The size of a mineral deposit, its proximity to the surface, and the relative simplicity or complexity of the beneficiation or advanced processing required appear to have had the greatest influence on total development cost. Itself influenced partly by deposit size and partly by market size, the desired rate of production has, of course, also been a factor. Some development costs for small, near-surface deposits are still small and comparable to those incurred in the development of gold deposits in the 1800's. Most, however, are much higher.

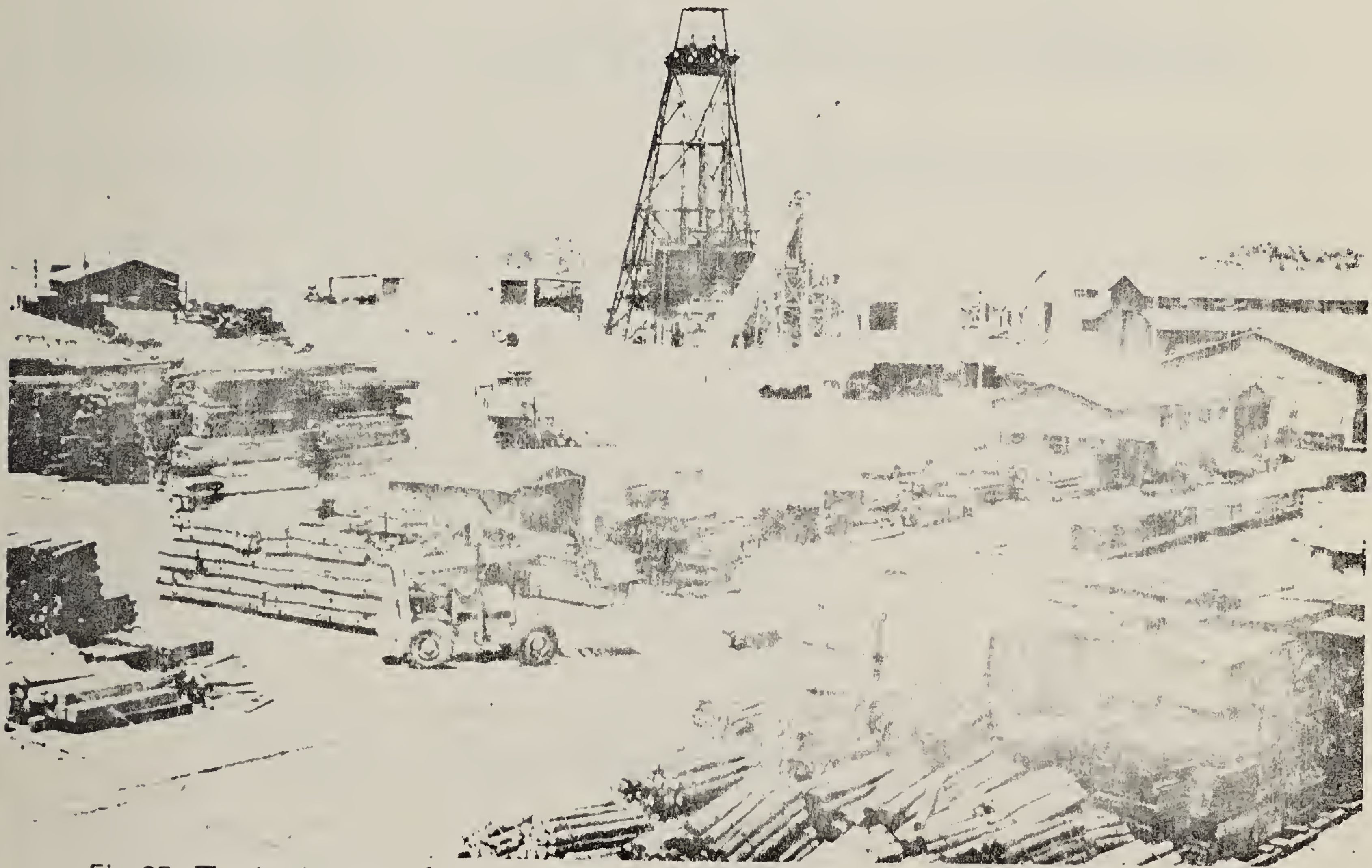


Fig. 25 - The development of deep orebodies for underground mining usually involves the installation of complex surface facilities even before development excavation can take place. This surface view of the main development shaft at San Manuel, Arizona, is an example of the surface facilities that sometimes may be involved even in underground development. This mine also has three other shafts in operation and two more being sunk. Not shown in this view are additional shops, warehouses, offices, and changehouse facilities that also form part of the surface plant needed for underground mine development.

Table 20

SELECTED DEVELOPMENT COSTS IN URANIUM MINERALS UTILIZATION, 1966

1. *Typical construction costs for an acid leach uranium processing plant:*

Rated Capacity (tons per day)	Estimated Cost (per daily ton of capacity)	Estimated Total Cost
500	$6,800-$8,300	$ 3,400,000-$ 4,150,000
1,000	4,700- 5,800	4,700,000- 5,800,000
2,000	4,100- 5,100	8,200,000- 10,200,000
5,000	3,100- 3,700	17,050,000- 20,350,000

2. *Typical stripping costs for an open pit uranium mine:*

	Range	Average
soft overburden	19 to 30c per cubic yard	25c per cubic yard
hard overburden	30 to 50c per cubic yard	40c per cubic yard

3. *Typical underground mine development costs:*

	Range	Average
surface plant	$150,000 to $800,000	$600,000
equipment	20 to 40c per ton	30c per ton
rectangular shaft	$300 to 400 per ton	$500 per foot
circular concrete shaft	$500 to 800 per foot	$650 per foot
bored shaft	$720 to 950 per foot	—
shaft stations	—	55c per cubic yard
wet drifts	$ 50 to 70 per foot	$ 60 per foot
dry drifts	$ 40 to 60 per foot	$ 50 per foot
raises	$ 30 to 60 per foot (depending on size)	—

Source of data: United States Atomic Energy Commission

Table 21

MINE DEVELOPMENT COSTS

A. *Analysis of Stripping Costs Based Upon 4,065,475 Tons Moved in Four Months of 1957 at Bagdad Mine*

	Percent of Total Cost
Direct Labor	3.06
Other Direct Charges	0.39
Primary Drilling	9.57
Secondary Drilling	1.11
Blasting Supplies	11.28
Loading	17.35
Haulage	45.78
Dozers and Graders	8.40
Miscellaneous	3.06
Total	100.00

Source: S.D. Woodruff, *Methods of Working Coal and Metal Mines*, New York: Pergamon Press, 1966. Vol. 3, p. 531.

B. *Estimated Stripping Costs at Open Pit Iron Mines in the United States and Canada*

Operations	Cost (in dollars per ton of ore mined)
Erie Mining Co., Minnesota	0.20
Reserve Mining Co., Minnesota	0.10
Empire-Cleveland Cliffs, Michigan	0.05
Groveland-Hanna, Michigan	0.10
Republic-Cleveland Cliffs, Michigan	0.20
Carol-Iron Ore Co., Canada	0.02
Quebec Cartier, Canada	0.24

Source of Data: J.K. Hammes, *The Economics of Producing and Delivering Pellets,* paper presented before the Minnesota Section, American Institute of Mining, Metallurgical, and Petroleum Engineers.

Table 22

INVESTMENT IN PRINCIPAL CAPITAL NEW MINING OPERATIONS[a] 1956 - 1966

Property	Commodity	Development Cost (millions of dollars)	Type of Mine	Product Capaci (tons p day)
Immel Mine, Tennessee	Zinc	3.9	Underground Mine, Mill	3,000
Gullbridge Mine, Newfoundland	Copper	2.7	Underground, Mill	1,500
Mission Mine, Arizona	Copper	33.0	Open Pit, Mill	15,000
Fletcher Mine, Missouri	Lead	11.5	Underground, Mill	5,000
St. Lawrence, Quebec	Columbium	2.8	Open pit, Complex flotation mill	1,000
Palabora, Transvaal	Copper	103.95	Open pit, Mill and Smelter	33,000
Alice Arm, British Columbia	Molybdenum	19.8	Open pit, Mill, Wharf, and Town	6,000
San Manuel, Arizona	Copper	119.0	Underground, Mill, and Smelter	35,000
Whalesback, Newfoundland	Copper	7.0	Underground, Mill	2,000
Cupra, Quevec	Copper	2.0	Underground, Mill	500
Ozark, Missouri	Lead	24.6	Multiple underground, Mill	6,000
Kidd Creek, Ontario	Copper-Lead-Zinc	25.2	Open pit, Mill	6,000
Lac LaRange,Saskatchewan	Copper	3.78	Underground, Mill	900
Carlin, Nevada	Gold	10.0	Open pit, Cyanidation Mill	2,000

Table 22 (Cont.)

ynagh, Ireland	Copper-Lead-Zinc-Gold	12.0	Open pit, Mill	2,000
hristmas, Arizona	Copper	24.0	Underground, Mill	4,000
io Blanco Mine, Chile	Copper	65.0*	Underground With Railroad, Harbor, Townsite	10,000
ixby Mine, Missouri	Lead	35.0	Underground, Mill and Smelter	5,000
logul, Ireland	Lead-Zinc-Gold	21.0	Underground, Mill	3,000
oquepala, Peru	Copper	237.6	Open pit, Mill and Smelter	33,000
attle Mountain, Nevada	Copper	21.9	Open pit, Flotation	3,000
chreiber, Ontario	Zinc-Copper	1.0	Underground, Mill	100
rand Duc, British Columbia	Copper	75.0	Isolated site, Underground, Flotation	7,500
otash Corp. of America, Saskatchewan	Potash	43.6	Underground, Mill, Shaft Sinking	4,000
ine Point, Northwest Territories	Zinc-Lead	120.0	Underground, Mill, with 432 Miles of Railroad and with Hydro-power Development	5,000
ima County, Arizona	Copper-Lead-Zinc	2.5	Underground, Mill	500

Since has been increased almost two times.

ost is reported as "Cost of Project" or "Capital Cost" and includes development, mine plant, mill, and in ome cases, smelter, townsite and other facilities.

ources of Data: *Engineering and Mining Journal, Mining Engineering,* and various other periodicals.

Table 23

REPRESENTATIVE MINE DEVELOPMENT COSTS IN THE UNITED STATES, 1947 - 1968

Mine (Ranked by Cost)	Commodity	Development Cost[a]
1	Lead	$19,000,000
2	Evaporite	5,000,000[b]
3	Lead	4,000,000
4	Sand	1,700,000
5	Iron	1,098,000
6	Potash	1,000,000
7	Uranium	510,000
8	Clay	415,000
9	Phosphate	400,000
10	Uranium	390,000
11	Uranium	286,000
12	Phosphate	200,000
13	Industrial Minerals	165,000
14	Uranium	75,000
15	Iron	70,000
16	Iron	50,000
17	Uranium	50,000
18	Salt	46,000
19	Phosphate	40,000
20	Limestone	28,000

[a] Cost from recognition as an orebody to first significant production.

[b] Largely pilot plant testing.

Source: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

4. Development Area Requirements

Just as the time and money requirements for mine development have changed since the period prior to 1872, so also have the spatial needs. The amount of surface area generally required for the mine development phase of mineral deposit utilization has likewise grown since 1947.

Several factors have contributed to the need for larger areas in the development stage of minerals utilization. Not the least of these has been the increasing importance of hydrometallurgical processes for minerals extraction. Among the most significant of the new methods has been dump leaching. While the practice of leaching old waste dumps has been followed for years, at many new mines the storage areas for waste rock are being specifically developed for dump leaching. In some instances this material, once considered waste, is now considered a class of ore, too low-grade for traditional beneficiation, but ore nonetheless.

Development for dump leaching is similar in most respects to the normal development of open pit mines. The leach material must be prepared for mining by removal of overburden. In most cases, leaching is carried out in conjunction with what have been the more conventional mining operations in which most of the ore that is mined is beneficiated to produce a concentrate. In a few mining operations, such as the Ranchers Bluebird operation at Miami, Arizona, the entire mine production is leached.

Leach dumps must be placed either on a solid, impervious rock base or on a prepared base that will serve to collect and divert the leach liquors to a holding pond or reservoir. Preparation of the leach pad consists of first removing all vegetation, leveling and grading the surface, covering it with sized crushed rock, compacting, and sealing with hot asphalt. Because a thinner bed of leach material normally accelerates the extraction process, the wider the area over which the given tonnage of rock may be spread, the better the operation of the process. This has created additional requirements for land areas for development as leaching dumps.

Another type of recently introduced process in minerals extraction has had an opposite effect on land requirements during the mine development stage. This is the method, similar to the long-used Frasch process for sulfur mining, called solution mining. Solution mining is currently in the experimental stage in the Shirley Basin in Wyoming where the Utah Construction and Mining Company is attempting to recover uranium. Solution mining of deep potash is already in the production stage at Kalium Chemical Company's mine near Regina, Saskatchewan.

Development in solution mining, as it is being practiced in these operations, consists mainly of drilling wells to intercept the mineralized horizons and then preparing some of these wells for injection of the recovery liquid (acid water is used in the recovery of uranium) and the remainder of the wells for pumping out the pregnant solutions. The wells must be cased to isolate the mineralized horizon from other permeable strata. Initially, wells are developed by high-pressure jets to establish communication of the fluids between the injection and recovery wells. This operation is continued until a satisfactory flow rate is established which will maintain the desired production. With wells providing the principal access to the mineral to be mined, the land area requirements of the mine development stage thus become more like those of petroleum and natural gas development. The needs for surface processing plants, of course, remain as in other types of mining.

Probably the most significant factor affecting the spatial requirements of mine development, however, has simply been the trend towards the utilization of larger deposits of lower-grade minerals. The development of larger deposits by open pit methods has, of course, made larger areas for stripping and overburden storage necessary in direct proportion to the size of the orebody itself. Even with underground development, the larger the deposit (and usually also the deeper the deposit) the greater the area needed for surface facilities. Furthermore, it is also true that the lower-grade deposits that have been developed since 1947 have had greater needs for surface space for the large beneficiation plants than the utilization of such mineral deposits has demanded. And, of course, all of this space must be available even if not in actual use before production from any orebody can begin.

Table 24

SPATIAL REQUIREMENTS IN MINERAL DEPOSIT DEVELOPMENT IN THE UNITED STATES, 1947 - 1968

Property (Ranked by Area Used in Development)	Commodity	Total Area (in acres) Involved in Development	Total Area (in acres) Covered by the Orebody
1	Clay	30,000	24,000
2	Phosphate	6,400	8,000
3	Lead	5,000	500
4	Phosphate	2,500	1,000
5	Salt	2,500	500
6	Copper	800	600
7	Lead	800	800
8	Beryllium	800	800
9	Lead	500	500
10	Copper	500	500
11	Lead	400	400
12	Uranium	300	20
13	Sand	300	300
14	Uranium	210	80
15	Copper-Silver	200	100
16	Gold-Silver	160	80
17	Copper	150	150
18	Gypsum	120	2,560
19	Barite	100	80
20	Copper	100	100
21	Uranium	80	80
22	Copper	60	60
23	Limestone	46	46
24	Uranium	20	1
25	Uranium	20	5
26	Iron	20	4
27	Gypsum	10	1,920
28	Gypsum	10	1,280
29	Uranium	7	4
30	Uranium	5	4
31	Uranium	2	2

Source: Survey conducted by the Division of Economic and Business Research, The University of Arizona.

E. CHANGES IN MINE DEVELOPMENT EXPECTED BY 1985

There is little doubt that the trends in mine development that have taken place in the United States since the end of World War II are likely to continue throughout the next two decades. The various characteristics of mineral deposit development will change, and they probably will change along directions already laid out. These changes will be governed by the physical features of the mineral deposits to be mined and by the technical and economic environments within which mine development must take place.

Mine development in the future will undoubtedly be more expensive as prices rise and the availability of near-surface orebodies diminishes. Mine development probably will not require any substantially greater length of time than at present, however. Technical innovations designed to speed development operations will probably offset increasing physical difficulties to keep development times relatively steady.

New mine development in the next two decades will probably require ever increasing land areas, but there will be some exceptions. The mineral industry of the United States appears to be on the threshold of revolutionary concepts in both mining and processing. The mining of deep mineral zones by chemical solution and pumping may be extended beyond the current practice in salt (sodium chloride) beds. One such departure has already begun in the Saskatchewan potash field. Nuclear explosives are under intensive consideration for the purpose of shattering buried orebodies so that the minerals may be extracted by chemical solution. Rapid stripping of overburden is under study. Offshore mining and the entire frontier of the sea have become a major attraction. The possibilities for extracting minerals from sea water, from the sea floor, and from deposits beneath the sea floor are intriguing, but current shallow and near-shore mining installations have pointed out the overwhelming problems involved in the broader marine environment.

The newly proposed mining methods have a common denominator which will require a relatively long pre-production interval, greater amounts of capital, and perhaps greater land area needs. The initial economic studies, the delineation of suitable reserves, and experimental mining are so costly that subsequent operations must be based upon large tonnages and low unit production costs. A large committment of capital and a thorough development program will be required for any future mine. As an indication of the time pattern to be met in nuclear mining, a proposed experimental effort, *Project Sloop*, at Safford, Arizona, would require nine months of intensive development work before the nuclear detonation, plus nine months of additional work before in-situ leaching tests could even begin. An experimental leaching program of at least one year would then be required in order to gain enough data for another year or more of performance evaluation. As new mining concepts begin to be utilized on an economic basis, each one must allow for a period of testing at the specific site, just as in the case of the proposed nuclear copper mining at Safford.

A well-made mine requires an orderly and complete development program, and a well-made mine provides for the best use of available mineral resources. With sufficient time and flexibility, competent miners can bring a profitable new industry into being where none existed before. With insufficient time and with inflexible pre-production conditions, a mine, if made at all, can only be poorly made and can then only attain a portion of its potential value. Such practice becomes a waste of both natural and human resources.

FOOTNOTES

45/ John E. Allen, *The Making of a Mine,* New Mexico Bureau of Mines, Circular 41 (1956), p. 3.

46/ T. A. Rickard, *op. cit.,* pp. 192-196.

47/ H. L. Bauer, *et al,* "Porphyry Copper Deposits in the Robinson Mining District, Nevada," *Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona (1966), p. 233.

48/ R. A. Metz and A. W. Rose, "Geology of Ray Copper Deposit," *Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona (1966), p. 177.

49/ C. H. Dunning, *Rocks to Riches,* Phoenix: Southwest Publishing Co. (1959), pp. 184, 200.

50/ A. W. Rose and W. W. Baltosser, "The Porphyry Copper Deposit at Santa Rita, New Mexico," *Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966), p. 205.

51/ H. W. Olmstead and D. W. Johnson, "Inspiration Geology," *Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona (1966), p. 143.

52/ L. J. Arrington and G. B. Hansen, *The Richest Hole on Earth,* Logan: Utah State University (1963), pp. 29-40.

53/ Allan B. Bowman, "History, Growth, and Development of a Small Mining Company," *Mining Engineering,* Vol. 15, No. 6 (June 1963), pp. 42-49.

54/ L. Telfer, "Time is of the Essence in Mineral Exploration," *Canadian Mining Journal* (April 1961), p. 68-70, and W. T. Irvine, "The Bluebell Mine," *Structural Geology of Canadian Ore Deposits,* Montreal: Canadian Institute of Mining and Metallurgy (1957), pp. 95-104.

55/ F. A. Knox, *Gold Mining in Ontario–Report of the Committee of Inquiry into Economics of the Gold Mining Industry,* Toronto: Ontario Department of Mines (1955), pp. 5-16.

56/ R. P. Douglas, "The Wedge Mine–Newcastle–Bathurst Area, New Brunswick," *Canadian Mining and Metallurgical Bulletin* (March 1965), pp. 290-296.

57/ T. F. Creamer, "The Commercial Banker's Function in Financing Mining Ventures," *Mining Congress Journal* (January 1960) and W. F. Boericke and C. C. Bailey, "Mine Financing," *Economics of the Mineral Industries,* New York: American Institute of Mining and Metallurgical and Petroleum Engineers (1964), Second Edition, p. 251.

58/ F. A. Rutledge, "Eximbank Financing in Latin America," *Mining Congress Journal,* April 1965, pp. 63-67 and Daniel Jackson, "Building New Coal Markets–The Union Carbide Approach," *Coal Age,* November (1964), pp. 60-71.

CHAPTER 9

THE PRODUCTION OF MINERAL COMMODITIES

Has the production of nonfuel minerals changed since the 1860's? Since 1947? Have any such changes since 1947 followed discernible trends which might be projected to 1985?

A. THE PRODUCTION PROCESS

1. The Phases of Mineral Production

All minerals production involves at least two phases, and in many instances, a third is also required before a saleable commodity can be created from the raw natural resources of the earth. The first phase is *mining*, the actual removal of the mineral from the earth's crust. The second phase involves physical preparation of the raw mineral for either sale or further processing and is termed *beneficiation*. This phase may involve merely washing or breaking and sizing the mineral material, or it may also involve physical methods of concentration to remove waste material and increase the valuable content of the remainder.

The third phase involves subjecting the mineral material to some type of chemical process in order to extract a valuable element (usually a metal) from its naturally occurring compounds, to purify a particular chemical substance, to alter the chemical composition of a naturally occurring mineral, or sometimes even to synthesize new compounds from the mineral raw materials. These may all be referred to as part of the *advanced processing* phase of minerals production.

As shown in Figure 24, the phases of mineral production flow from the exploration and development phases previously discussed. As also shown, each of the three major phases of production is composed of a number of minor stages which likewise follow one upon another. These are normally referred to as *unit operations*.

2. Mining Operations

All mining methods involve two fundamental tasks – breaking the ore, and transporting it to the beneficiation or processing plant. Regardless of the scale of the mining enterprise, whether it be an enormous open pit mine with its mammoth equipment or a small underground mine, the same unit operations of mining are performed. Historically, ore breakage in mining has been performed in a conventional drill and blast cycle. This cycle involves drilling holes in the solid rock with mechanical drills, loading the holes with explosives, and detonating the explosives to break the rock. While drilling equipment used in underground mines where space is restricted varies considerably from large open pit machinery, the basic principles of the operations are identical.

Continuous breaking, rather than cyclic breaking with a drill and blast operation, is predominant in "soft" rock mining today and has been used since the day the pick and shovel were invented. The continuous breaking methods essentially involve the application of a mechanical force to the virgin rock in place, now usually in the form of rotating cutters or chain-saw type devices. While continuous excavation methods have been more competitive in underground mining, large continuous excavators have also been used successfully in surface mining.

Recent advances in excavation technology have resulted in large machines also capable of boring through hard rock continuously, although the economics of these machines have so far prevented their adaptation to actual volume production. Boring machines are, however, becoming popular for underground mine development work.

Once the ore is broken, it then must be transported to the beneficiation or processing

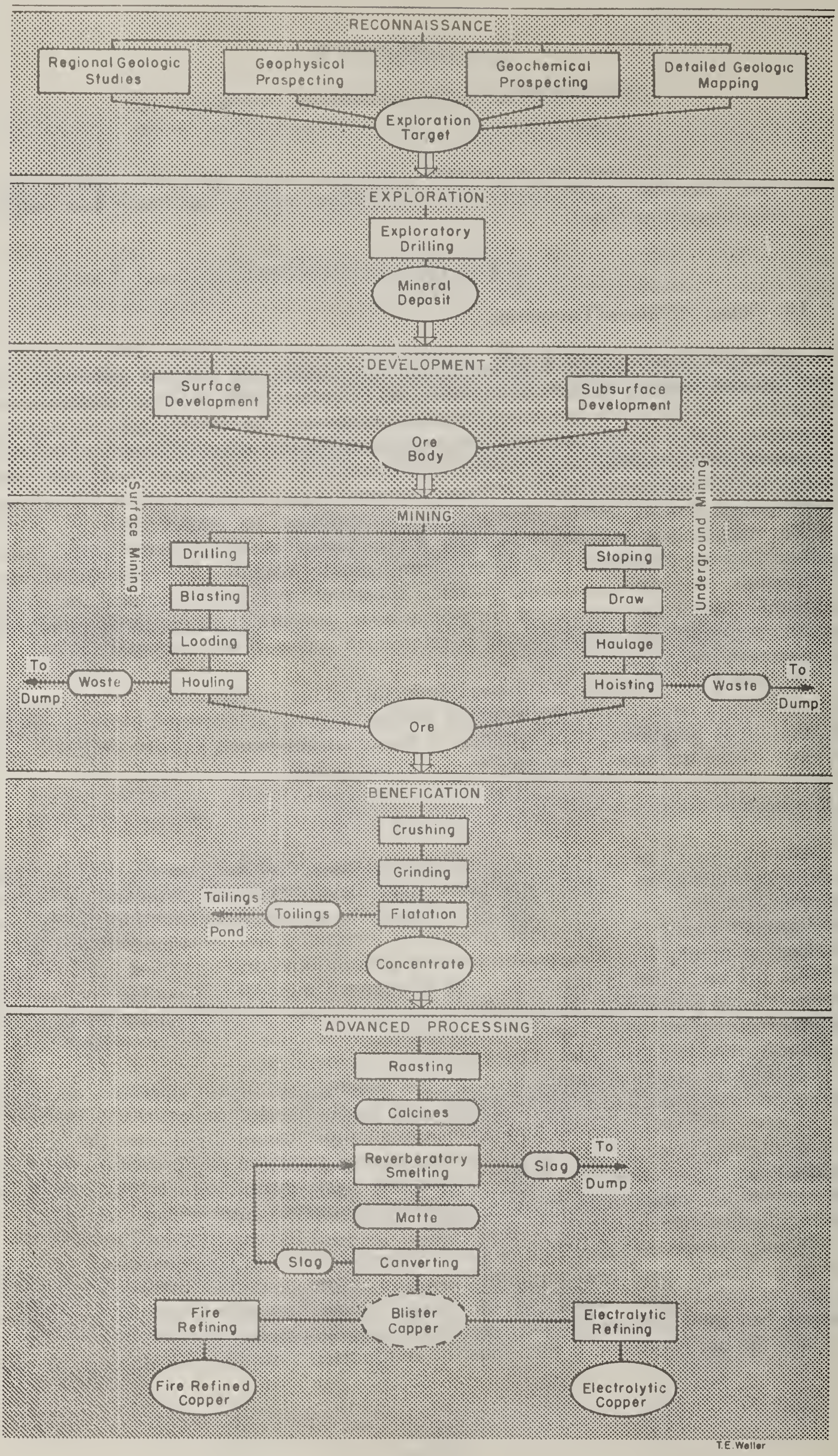


Fig. 26 - The process of finding and using a copper mineral deposit. The major phases of the process

Quarries tend to be worked in a single bench or high wall because the traditionally quarried varieties of rock commonly occur as strata with the only valuable or desirable rock commodity confined to a single horizon. The thickness of the economic horizon may not be sufficiently great to warrant multiple bench development, but it may be thicker than desirable for a single bench operation. The width to be mined in fact may vary considerably. Thus the bench or wall in a quarry tends to be higher or lower than in open pit mines where multiple bench development permits a specific selection of bench height. Quarries, also, are normally not as deep for their lateral dimensions as are open pits. This is caused both by the layered occurrence of most quarry deposits and their comparatively low value and selling price. The price of building stone or aggregate normally will not support the stripping of as much overburden as even low-grade copper ore. Furthermore, quarry products must be mined comparatively close to markets because of their bulk and low unit value.

Strip mining, also called *opencast* or *surface mining* by some, is the term most frequently applied to the surface mining of coal. Both terms, strip mining and opencast mining, are sometimes erroneously used synonymously with open pit mining and opencut mining. While strip mining has many features in common with open pit mining and quarrying, both strip mining and dredging have the more or less unique and distinguishing feature of filling in previous excavation as mining progresses.

Strip mining essentially involves removing the overlying strata or overburden and extracting the valuable mineral deposit. The mineral occurrences to which this method is applicable are characteristically tabular, flat-lying, and relatively shallow, such as deposits of coal, clay, sand, gravel, and some uranium, phosphate, and placer deposits. In most instances the overburden, as it is removed from one portion of a mineral deposit, is used to fill in the hole left by the previous removal of another portion of the deposit. The disposition of waste overburden is thus much less of a problem in strip mining than in other types of surface mining where the vertical dimension of a deposit does not permit its complete removal from an area in one mining cycle.

The removal of overburden is an auxiliary unit operation in virtually all surface mining enterprises. It has its counterpart in underground mining in the removal of waste from haulageways and other openings driven in waste rock rather than in ore. Overburden removal is, nevertheless, a vital part of the surface mining method. Where the overburden is rock, blasting is necessary to prepare it for loading by shovels. Where the overburden is unconsolidated, it can be removed directly by dragline, scraper, or other excavators. The usual method used in overburden removal entails a series of slices or cuts. The length of each cut is governed by the width of the deposit to be mined at one time. The width of the cut is governed by the size and type of excavating equipment used. Shovels and draglines can cast and lift material only so far, so there is a limited amount of material in a given cut that can be moved at one time without expensive rehandling of the material.

The initial cut in a strip mine is called a *box cut.* The waste material from this cut must be loaded and hauled away for disposition. The exposed mineral can then be excavated. As the second cut is made, the overburden is placed in the void left by the first cut, exposing the mineral deposit in the second cut. This sequence of operations is repeated until the entire deposit is worked out. Strip mining thus leaves behind a ridged surface somewhat higher in elevation than the original ground level. If the spoil from the box cut is used to fill in the final cut, no empty excavation remains from this method of mining.

Placers are defined frequently as unconsolidated deposits of detrital material containing valuable minerals, and placer mining is the surface removal of the minerals from placer deposits. A unique characteristic of placer mineral production is that the mining phase usually is accompanied immediately at the mining site by primary beneficiation using wet gravity methods to physically separate the heavy mineral sought from the lighter sand and gravel.

Methods of mining placers, based on the method of excavation, may be classified as land based operations, in which either hand tools, powered equipment or water are used, or as floating plant operations in which a dragline and floating washing plant, bucket-line dredge, or hydraulic dredge may be used. Regardless of the specific method of placer mining area. The normal sequence of events involves loading the ore into some haulage conveyance for transportation directly to the beneficiation area, or as is often the case in underground mining, to a shaft for hoisting to the surface from whence it is taken to the beneficiation plant. The scale on which loading and haulage are performed varies enormously from surface to underground mining, but these unit operations are functionally similar regardless of the type of mine involved.

Underground ore transportation is often more complex than the transportation systems used in surface mines, for in some mining methods the ore must be handled (loaded and hauled) two or perhaps three times. In cut and fill stoping, for example, the ore must first be transported to the ore pass in the stope. Then it is reloaded at the haulage level, and if the ore must be hoisted, it is reloaded again in skips at the shafts. In some underground mines, however, advancing technology has allowed the simplification of these operations. The continuous mining machines used so commonly in coal and potash mining combine the ore-breaking operation with the loading task. This is also true of the horizontal hard-rock boring machines used in some mine development work today.

3. Auxiliary Unit Operations

Depending on the mining method used, one or more auxiliary operations may be encountered. These functions are not basic in that they do not directly involve the removal of the ore for beneficiation, but they are often essential to the safe and economic recovery of the ore. Good ventilation is obviously required for safe underground mine operation. In some mines, mainly those known to be working deposits containing explosive gases and those operating in extremely hot rock temperatures, extension of the ventilation system is a standard part of the mining operation. In other mines, ventilation changes are made less frequently but are nonetheless important. In all underground mines the quality and quantity of ventilating air are checked on a regular basis.

The provision and maintenance of roof support is a vital unit operation in many underground mining systems. Mining in weak, incompetent rock often requires immediate support of the roof after the ore is removed. There are a variety of support methods available for use, with timbering (with both wood and steel), concreting, and rock bolts being the most common. Scaling is a minor unit operation found in many mining cycles that is closely related to roof support. This task involves prying down loose slabs of rock that remain on the face or back after blasting that might present a safety problem during the ore loading cycle. Backfilling is another related unit operation in those underground mines that fill mined out stopes with waste rock. Waste fill provides strong permanent and economical support for stope walls. In competent rock formations, however, artificial support, such as waste fill, is seldom used.

Surface mining methods also involve some auxiliary operations that are not themselves directly involved in the removal of ore itself from the ground. These operations are relatively consistent, regardless of the type of surface mining being done or what that surface mine may be called.

4. Surface Mining Methods

A *quarry* is usually defined as an open or surface working for the extraction of rock, such as building stone, decorative stone, slate, aggregate, limestone, silica, metallurgical fluxes, and the like. The surface mining of such nonmetallic materials that are valuable chiefly for their physical properties is thus commonly called *quarrying,* as distinguished from the *open pit mining* of metalliferous deposits and the strip mining of coal or other comparatively thin-bedded and flat-lying deposits. Regardless of the nomenclature, these methods have far more in common than not. They all go through the same stages in the creation of a mining operation. They all have either the same or similar unit operations, from rock breaking or loosening through loading and hauling, and each results in an excavation or open working at some stage of production.

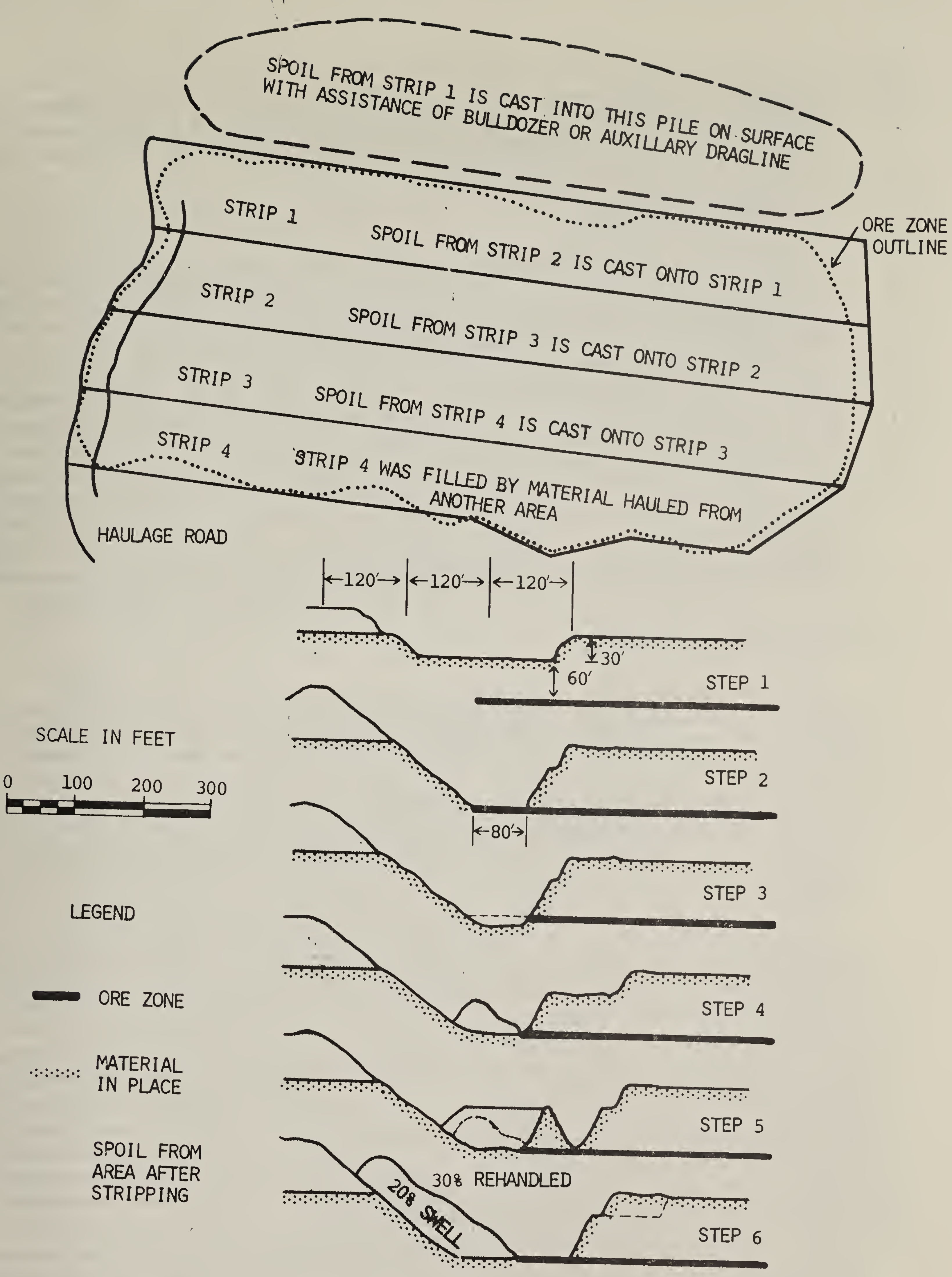

SPOIL FROM STRIP 1 IS CAST INTO THIS PILE ON SURFACE WITH ASSISTANCE OF BULLDOZER OR AUXILLARY DRAGLINE
STRIP 1
SPOIL FROM STRIP 2 IS CAST ONTO STRIP 1
ORE ZONE OUTLINE
STRIP 2
SPOIL FROM STRIP 3 IS CAST ONTO STRIP 2
STRIP 3
SPOIL FROM STRIP 4 IS CAST ONTO STRIP 3
STRIP 4
STRIP 4 WAS FILLED BY MATERIAL HAULED FROM ANOTHER AREA
HAULAGE ROAD
120′
120′
120′
30′
60′
STEP 1
STEP 2
80′
STEP 3
STEP 4
STEP 5
30% REHANDLED
20% SWELL
STEP 6
SCALE IN FEET
0
100
200
300
LEGEND
ORE ZONE
MATERIAL IN PLACE
SPOIL FROM AREA AFTER STRIPPING

Fig. 27 - Sequence of operations in strip mining. This method is restricted to a select number of mineral commodities (e.g., coal and pebble phosphates) that occur in relatively thin, horizontal beds close to the surface. A distinguishing feature of the method is that it involves filling the previously excavated hole with overburden stripped from new "ore" as mining progresses.

employed, however, the basic process is essentially similar to mining by other surface or underground methods. In each, the valuable mineral is broken or loosened (i.e., placed in a fluid-solid state), then loaded onto some means of conveyance, and then transported to a beneficiation or advanced processing plant.

5. Other Mining Methods

Even modern solution mining and in-place leaching processes follow this same sequence of operations. The principal methods of leaching used at present are *dump, heap, in-place* (or *in-situ*), and *vat*. These methods are interrelated, and many items considered necessary for effective leaching by one method are applicable to the other methods.

In-place leaching involves the leaching of broken ore in the ground as it occurs. Much current in-place leaching employs the dissolution of copper minerals contained in underground mines that previously utilized block-caving mining methods. Although heap, dump, and vat leaching may perhaps be more properly considered advanced processing methods since they are chemical processes used to extract metal from rock that has already been removed from the earth, in-place or in-situ leaching is an actual mining operation. In this type of leaching, as well as in the Frasch process for mining sulfur and in the methods of solution mining used to recover various evaporite minerals, the mineral sought is converted to a fluid state, collected, and pumped from the ground. The techniques, equipment, and nomenclatures are different, but the principles are basically the same.

6. Beneficiation Operations

The beneficiation phase of minerals production, like the mining phase, consists of a number of minor processes. Unlike mining, however, the principles involved in some of these unit processes may differ widely from one commodity to another. Some, however, are basic to all (or nearly all) minerals.

Metalliferous minerals are usually not found in pure form. They are most often mixed with rock and other unwanted materials, and are usually found as compounds of several elements. Physical separation of the various mineral compounds is the first of many beneficiation steps that eventually provide the concentrated mineral needed. Crushing, grinding, classifying, and some kind of concentrating are the steps normally used.

After mining and before actually separating the valuable ore minerals from the gangue minerals, the ore must first be prepared. First, the ore mineral grains must be liberated from the gangue minerals by washing, and/or crushing and grinding. Second, if it is necessary, the minerals must be classified to a predetermined particle size which best suits the particular concentration process to be used.

Concentration, or the separation of mineral mixtures into two or more products each having a specific composition, is possible because of differences in various properties of the minerals. For example, the differences in color and luster are utilized in hand picking while differences in density permit separation by various methods of gravity concentration and differences in magnetic properties permit concentration by the use of electro-magnets. Impure metals are then extracted from high-grade ores and concentrates by advanced processes known as pyrometallurgical or hydrometallurgical processes and then refined by these same processes, or by electrometallurgical processes.

The recovery of metals from ores is, for the most part, a series of step-by-step processes, and the recovery of some metals requires more steps than others. Usually each unit process is designed to lead to another until the most useful form of metal is produced. The process of crushing ore, for instance, most often leads to grinding, and grinding leads to classification, and so on through all the processes necessary to produce the metal desired. But in some cases, crushing leads to leaching, or calcining, and a different route to the desired product may be taken.

Most metalliferous ores are not rich enough in metals or low enough in detrimental impurities to permit direct chemical extraction of their valuable content. Consequently, these ores undergo beneficiation processes which are the mechanical processes involved in changing raw ore (usually low-grade ore) to an enriched material called *concentrate*. Beneficiation is also often called ore dressing, milling, or mineral dressing.

There are two distinct advantages in making a concentrate from low-grade ore. First, mechanical methods of rejecting waste material are usually cheaper than chemical methods. Second, the rejected waste material which can be removed does not have to be shipped, which saves freight costs. There are a few beneficiation steps which most metalliferous minerals undergo before they are concentrated, and these include the unit processes of crushing, grinding, and sizing.

Crushing and grinding are almost always done in two or more stages using different kinds of machines, because such multi-stage size reduction has been found less expensive and more efficient. In crushing and grinding circuits, there are also several types of sizing devices which may be found. Primary crushers are designed to accept a maximum size ore and sometimes *grizzlies* (heavy gratings) are used to prevent oversized ore fragments from entering the crushers. Screens are used to pass finely crushed material to the next processing unit and to return oversized particles for recrushing. *Classifiers* also effect a size separation by taking advantage of the different settling rates in a fluid of particles which have varying shapes, sizes, and densities. The chief use of classifiers is to recirculate oversized particles back to a grinding unit.

The concentration of ore may actually start in the mining operation, using conventional methods, by selectively mining ore away from waste. Some ores may be broken and upgraded simply by washing to disintegrate and float away adhering clay or other fine grained material from the coarser portion of the ore. As an example, iron-bearing material containing clay and sand mixed with coarse hard iron minerals is often beneficiated simply by washing.

Industrial minerals are generally low-priced commodities which cannot stand expensive beneficiation or advanced treatment. Although some of the processes for extracting and upgrading industrial minerals have become highly technical, they are generally less complex than those used with metalliferous ores. Many industrial minerals are only crushed and sized before going on to the advanced processing phase while others may be only sized and washed before being sold. Some, however, such as phosphates, must also be concentrated in a manner similar to the production of metallic mineral concentrates.

7. Advanced Processing Operations

In the advanced processing phase of mineral production, various chemical processes are used to extract a valuable commodity from its natural compounds, to purify it, and/or to produce other useable chemical compounds or substances. In these advanced processing operations, the chemical reactions involved, and thus the various stages of the process itself, are often quite different, with considerable variation from one commodity to another. Certain unit processes, however, are widely used in the production of various commodities.

Ores or concentrates derived from the several processes of beneficiation generally require further treatment. Many metals are extracted from their ores and concentrates by *pyrometallurgical* methods. The extraction of metals from ore and concentrates by pyrometallurgical methods, for the most part, involves a series of step-by-step unit operations, with the recovery of some metals requiring more operations than others. Usually each operation is designed to lead to another until the most useful form of the metal sought is acquired. For example, the *smelting* of an ore or concentrate often leads to a process of *converting* and subsequently to *refining* if that is necessary to produce the metal desired.

Pyrometallurgy means, literally, fire metallurgy and involves such processes as roasting, smelting, and refining or any heating process used as the means to effect metal recovery. Practically all iron and steel, nickel, tin, most copper and a large proportion of zinc, gold, and silver, as well as many of the minor metals are won from their ores and concentrates by

Table 25

EARLY ORE TREATMENT METHODS
(known prior to 1872)

Process	Date of Initial Development
Gold washed from alluvial	Prior to recorded civilization
Copper reduced from ores by smelting	Prior to recorded civilization
Tin reduced from ores by smelting	Prior to 3500 B.C.
Iron reduced from ores by smelting	Prior to 3500 B.C.
Soda mined and used	Prior to 3500 B.C.
Gold reduced from ores by concentration	Prior to 2500 B.C.
Silver reduced from ores by smelting	Prior to 2000 B.C.
Lead reduced from ores by smelting	Prior to 2000 B.C. (perhaps prior to 3500 B.C.)
Silver parted from lead by cupellation	Prior to 2000 B.C.
Steel produced	Prior to 1000 B.C.
Base metals separated from ores by water concentration	Prior to 500 B.C.
Gold refined by cupellation	Prior to 500 B.C.
Sulfide ores smelted for lead	Prior to 500 B.C.
Mercury reduced from ores by . .(?)	Prior to 400 B.C.
Quicksilver reduced from ore by distillation	Prior to Christian Era
Silver parted from gold by cementation with salt	Prior to Christian Era
Zinc oxides obtained from furnace fumes by construction of dust chambers	Prior to Christian Era
Antimony reduced from ores by smelting (accidental)	Prior to Christian Era
Gold recovered by amalgamation	Prior to Christian Era
Refining of copper by repeated fusion	Prior to Christian Era
Sulphide ores smelted for copper	Prior to Christian Era
Copper refined by oxidation and poling	Prior to 1200 A.D.
Gold parted from copper by cupelling with lead	Prior to 1200 A.D.
Gold parted from silver by fusion with sulfur	Prior to 1200 A.D.
Gold parted from silver by nitric acid	Prior to 1400 A.D.
Gold parted from silver with antimony sulfide	Prior to 1500 A.D.
Gold parted from copper with sulfur	Prior to 1500 A.D.
Silver parted from iron with antimony sulfide	Prior to 1500 A.D.
Silver recovered from ores by amalgamation	Prior to 1500 A.D.
Separation of silver from copper by liquation	Prior to 1540 A.D.
Roasting copper ores prior to smelting	Prior to 1550 A.D.
Stamp-mill used	Prior to 1550 A.D.
Bismuth reduced from ore	Prior to 1550 A.D.
Zinc reduced from ore (accidental)	Prior to 1550 A.D.

Source: Georgius Agricola, *De Re Metallica*, translated from the first Latin edition of 1556 by Herbert C. Hoover and Lou H. Hoover; New York: Dover Publications, Inc., 1950, p. 354.

pyrometallurgical methods. It is the most important and the oldest of the extractive mineral processes.

Some of the pyrometallurgical unit operations include *drying* (in which moisture is removed from solid ore, concentrate, or flux), *calcining* (in which solid material is heated to drive off volatile components), *roasting* (in which heating involves a chemical reaction to produce a gas from certain components of the solids), *sintering* (in which heating causes an incipient fusion of finely divided solid particles to form a porous cake), *distillation* (in which heating causes vaporization and subsequent condensation of the metal to be recovered), *smelting* (in which heating puts ore or concentrates and flux into a liquid state), *converting* (in which liquid metal-bearing material is oxidized to remove or separate most of the impurities from the metal), and *fire refining* (in which impure liquid metal is generally oxidized to eliminate the impurities which can be readily separated from the purified liquid metals).

Some mineral commodities, such as a number of the industrial minerals, need only be dried before they are marketed. Metalliferous ores and concentrates, however, are sometimes dried because they contain sufficient moisture after beneficiation to reduce the efficiency of the advanced process to follow. Roasting or smelting furnaces may serve as driers, but drying as a separate operation is sometimes necessary to improve efficiency. Often a process will require dry material. Moist converter flux, for example, will react explosively with the liquid matte in a copper converter, and therefore must be dried first.

Calcining is a pyrometallurgical process that is also applied to a number of industrial minerals, particularly those which occur as carbonates or which naturally contain water molecules within their crystalline structures. Limestone and gypsum, for example, are commonly calcined in the first (and sometimes only) stage of their advanced processing.

Hydrometallurgy is the treatment of ore, concentrates, and other metal-bearing materials by wet processes, usually involving the solution of some component and its subsequent recovery from the solution. The dissolution of the valuable metals is called *leaching* and the metals are recovered from leach solution by *precipitation, ion exchange* methods, or by *electrolysis*. Copper, gold, silver, and uranium are the principal metals recovered by hydrometallurgical processes in the United States. These metals may be recovered by other processes, however, depending upon the physical and chemical properties of the particular ore being treated.

Amalgamation is the production of an amalgam or alloy of mercury and is considered a hydrometallurgical process although it does not involve water and does not resemble other types of leaching operations. Native gold and silver are sometimes concentrated by amalgamation methods. Clean gold or silver, when brought into contact with liquid mercury, will alloy to form mercury-coated particles which have surface properties similar to those of pure mercury. In amalgamation this alloy is treated by distillation and the gold and silver subsequently recovered.

Electrometallurgy is a term covering the various electrical processes for the industrial working of metals. It includes the extraction and refining of metals by use of electric currents and the operations in electric furnaces where electric current or arcs are used to supply heat. *Electrolysis* involves the extraction and refining of metals by use of electric currents and includes the electrolysis of aqueous solution as well as the electrolysis of igneous fusions or molten salts. The electrolysis of aqueous solutions includes the electrolytic extraction of metals from leaching solutions by electrolysis (*electrowinning*) and the electrolytic refining of metals.

Various other chemical processes, some complex, some relatively simple, are also used in the advanced treatment of mineral commodities. Some minerals may be subjected to many different processes, depending upon the nature of the desired product. The requirements of the market and the characteristics of the naturally-occurring mineral both dictate the method or methods of advanced processing that will be used in mineral production.

B. MINERALS PRODUCTION PRIOR TO 1872

1. Phases of Production

Minerals production in the United States in the 1850's and 1860's was conducted mostly on a small scale by large numbers of individual miners and small mining companies. The processes used were generally less complex than those of today and required far more manual labor. Nevertheless, many of the minerals production processes were basically identical, at least in principle, with those of the present.

In the mining phase of production, then as now, the mineral-bearing rock was broken or loosened, loaded onto some means of transportation, and transported to the beneficiation plant. There it was reduced in size to free the desired minerals from the gangue matrix in which they were found, and then it was treated further, if necessary, to recover the particular commodity sought.

While the basic procedures of mining, beneficiation, and advanced processing were in existence prior to 1872, the specific methods and techniques used were quite different and varied from one commodity to another. Although iron, copper, and lead as well as some industrial minerals were being mined in the Eastern United States in the 1850's and 1860's, the principal minerals mined in the West were gold, silver, and mercury. The modes of occurrence and high unit values of the ores mined were reflected in the mining methods used.

2. Placer Gold Mining

Placer gold deposits were among the first major mineral deposits discovered and worked in the West, and the technology of placer mining quickly grew throughout the region. In addition to the early deposits in the central valley of California, placers were discovered in Gold Canyon in Nevada in 1849, in Southwestern Oregon in 1850, at Gila City and LaPaz in Arizona prior to 1858 and in 1862, respectively, on the North Fork of the Clearwater River in Idaho in 1860, in Colorado in 1858, near Old Fort Colville, Washington, in 1855, along Gold Creek in Powell County, Montana, in 1852, in Lincoln County, New Mexico, in 1865, and in Bingham Canyon, Utah, in 1864. The Utah discovery was unusual in that the lodes from which the placers derived were discovered in 1863 before the discovery of the placers.

As the rich surface placers were washed out, lower-grade placers became of interest. In 1852, just four years after the commencement of the California gold rush, the hydraulic gold mining industry came into existence in that state. The newer mining method was based on the use of directed, high-pressure streams of water to rapidly excavate and make available for gravity concentration large amounts of auriferous gravel. The method was cheap and permitted the working of large bodies of gravel at a profit even when their gold content was only 10¢ per cubic yard or less.

Some of the larger placer deposits were worked underground. Drift mining in ancient buried stream channels was started at Forest Hill in Placer County, California, in 1852 and was an important source of placer gold by 1866. During the 1860's and continuing to about 1890, the drift or underground mining of placers was most productive.

Nevertheless, hydraulic mining quickly became and remained for much of the period before 1872 the dominant form of placer mining. In the hydraulic method, a high-pressure stream of water was directed against a bank of loosely consolidated gravel through a hose and nozzle device known commonly as a *giant*. A giant was capable of a colossal amount of clearing. With a nozzle three inches in diameter and when supplied with adequate water pressure, it could wash as much as 600 cubic yards of gravel in ten hours, with only three men required to operate it. At first the miners thought that the quantity of water they pushed through the pipe depended on the height from which they could take it rather than on the shape and form of the hose and the nozzle as well. But early troubles were not with the necessary lessons of hydraulics but with the hose itself. The strongest duck and leather hose would not hold more than about 80 feet of water pressure and was usually worn out

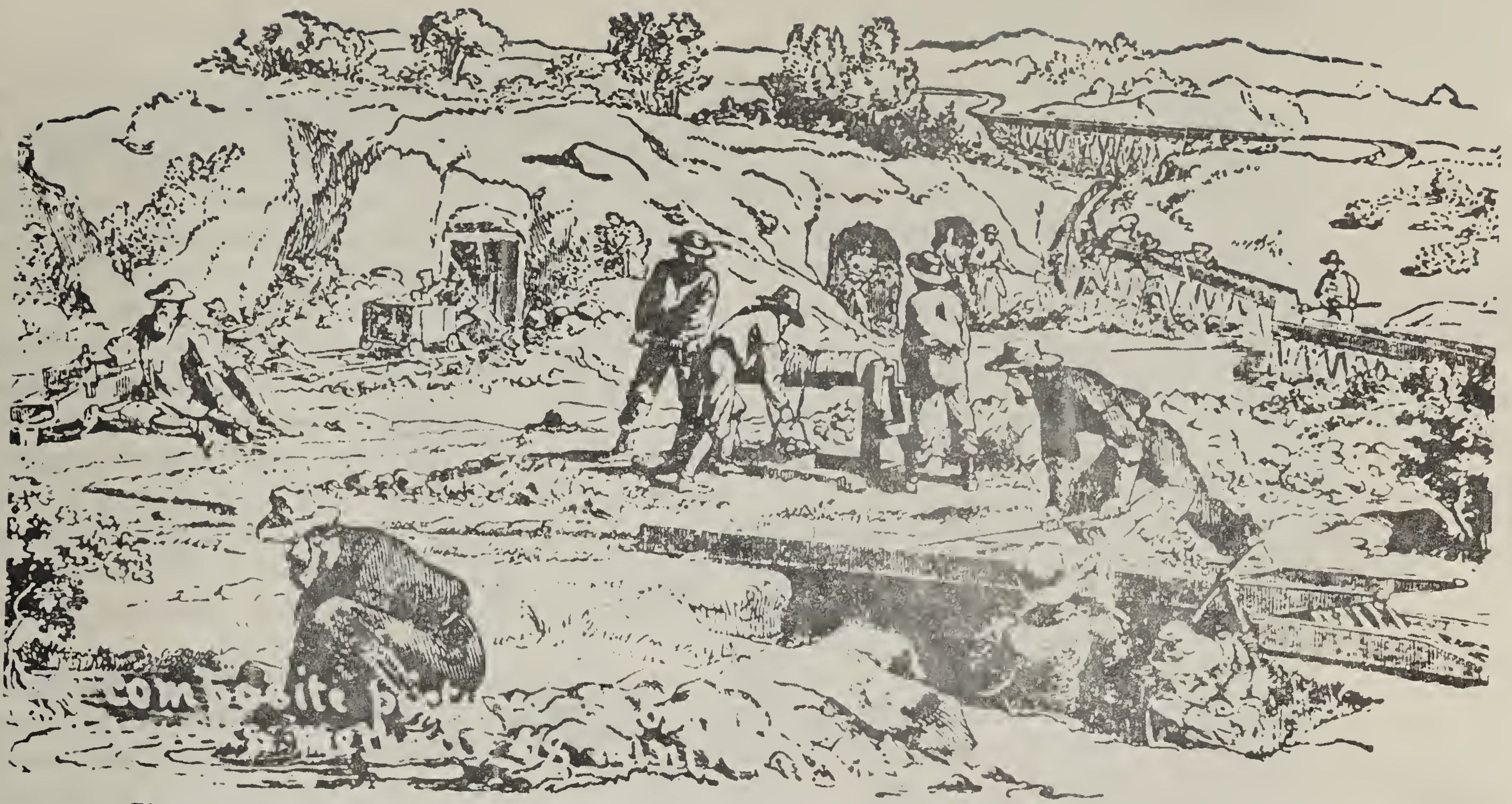


Fig. 28 - Early methods of mining gold in the placer deposits of Central California. Such methods usually required intensive use of manpower and water, but relatively little surface area aside from that immediately occupied by the mineral deposit itself. (Photo courtesy of Arizona Pioneers' Historical Society)

after only a few months of operation. So in 1861, some miners began experiments with "crinoline" hose strengthened by iron bands set at regular intervals. Nevertheless, the two most sophisticated techniques that developed were machines known as the *hydraulic elevator* and the *rubble hydraulic elevator.*

The hydraulic elevator utilized a powerful jet of water directed up the center of an inclined pipe. With the intake for the gravel near the mouth of the jet, the gravel was then forced up the throat of the inclined pipe. The rubble hydraulic elevator consisted of a chute about 100 feet long, inclined at an angle of about 20 degrees to the horizontal. The chute had a solid bottom along the lower 20 feet, but the upper section was fitted with transverse grizzly bars set a few inches apart. The working giant drove the gravel to the foot of the elevator, from which point a second giant drove the material up and over the grizzly. A further development of these hydraulic elevator techniques involved sinking a shaft into the heart of a placer deposit, then the giants were brought in and washed everything down to the bottom of the workings, where a series of sluices carried the gravel away.

Early placer mining, particularly by hydraulic techniques, required large amounts of water throughout the operating cycle. Considerable water was therefore diverted from other actual and potential uses to permit the production of placer gold. Moreover, the effluvia discharged by the giants silted stream channels, promoted flooding, and seriously hindered the development of agriculture on the flood plains. Farmers were incensed and legal battles over rights followed, leading to an avalanche of legislation forbidding hydraulic mining on navigable rivers anywhere in California. Even on those streams where it was permitted, the offensive detritus had to be removed. To do this, water wheels were installed and driven by steam to carry the tailings from a reservoir built below the sluices to flumes at a higher elevation. These flumes then discharged the stuff to some unfrequented and forgotten gulch. The high costs involved in treating this waste forced many hydraulicers out of business.

3. Other Precious Metal Mining

The importance of placer gold mining, however, soon gave way to hard-rock or lode mining. Kit Carson and two associates discovered the Mariposa Mine, a lode gold deposit, in California in 1849 and it was put into production the same year. Gold-bearing quartz was found on Gold Hill at Grass Valley in the Mother Lode country of California in June, 1850, and was so rich and gold so plentiful there that for a time the miners feared gold would lose its value. The first gold quartz claims were located on the Mother Lode in Amador County, California, in 1850 and probably during the same year in the other mining counties.[59]

In Nevada, the search for the sources of placers led to the discovery of the gold and silver veins of the Comstock Lode in 1859, and in Arizona, to the discovery of the Vulture Mine in 1863. In Idaho, gold quartz discoveries were made in 1862 near Placerville, in 1863 at Rocky Bar and Silver City, and in 1864 at Atlanta. Nevertheless, major gold production from quartz lodes in Idaho did not begin until the 1880's.[60] Lode gold mining did not commence in Washington until the 1870's, locations being made in Okanagan County in 1871 and in the Index and Blewett districts in 1874. The first lode mine in Montana is said to have been discovered in 1862 in the Bannock District. In New Mexico, gold-quartz veins were discovered at Hillsboro in 1877.[61]

The development of the lode deposits was generally much slower than that of the placer deposits due to the comparative difficulty of production from the lode deposits and to the hazards presented by hostile Indians in some regions. By 1865, placer deposits were being worked in nearly all the Oregon districts of prominence known today, but lode mining did not really develop until 1882-1888, after production had declined markedly from placers. Guerilla warfare waged by hostile Indians made it virtually impossible to operate mines in Arizona until the 1870's. Prior to this date, only one lode gold mine of importance was worked in the Territory. In 1872 large reservations were set aside for the Indians, but the price of gold was low and production from lode gold deposits in Arizona did not really get started until the fall of other commodity prices (and the resultant rise in the price of gold) in 1884.

In Arizona and New Mexico, silver mining had been carried on prior to the Gadsden Purchase, and the whereabouts of the silver mining districts were known to some United States citizens interested in mining. Charles Poston and Herman Ehrenberg, a mining engineer and a metallurgist, reconnoitered some of the old silver districts of Southern Arizona as early as 1854, the year of the Gadsden Purchase. On the basis of their observations and sampling, they organized the Sonora Exploring and Mining Company, with $100,000 cash. The company subsequently acquired the Arivaca Ranch of 17,000 acres in Southern Arizona which included some 80 mining claims. The company operated several mines, some of them through its subsidiary, the Santa Rita Mining Company.

Mining in Southern Arizona and New Mexico came to a virtual standstill during the Civil War, primarily because of the lack of troops to protect prospectors and miners from hostile Indians. It did not take long after the end of the war for interest in mining in these territories to be rekindled, however, and silver deposits were again sought. In the 1870's the McCracken, McMillenville, Richmond Basin, Silver King, Peck, Tip Top, and Tombstone deposits were found in Arizona. These were all principally valuable for silver.

Lead-silver deposits were one of the two most important sources of silver in the West during the period from 1860 to 1880, but it was not until after the coming of the railroads that lead became an important factor in the evaluation of such deposits. Even then it was still silver which was sought, with lead considered an important by-product. Zinc did not become important in the evaluation of base metal-silver deposits until much later.

4. Early Copper Mining

The situation was different with copper. In a few instances in the period from 1860 to 1880, copper deposits were sought solely or primarily for their copper content. Outcrops of

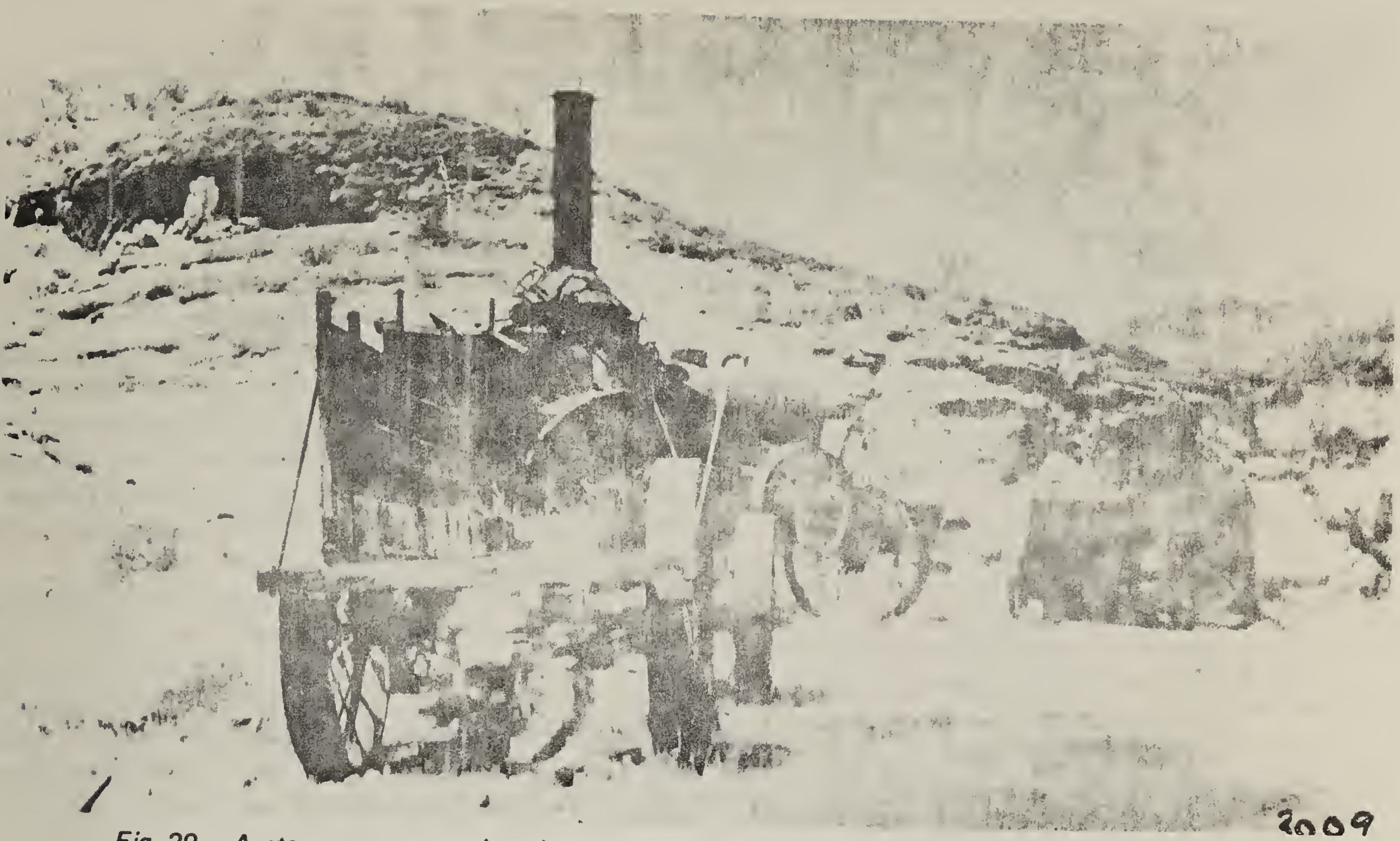


Fig. 29 - A steam wagon used to haul ore from the mine at Ajo, Arizona. Before the advent of rail equipment and modern trucks, such haulage equipment was common in the Western mining districts. (Photo courtesy Arizona Pioneers' Historical Society)

rich copper ores were known in Arizona and New Mexico for years prior to the California gold rush. Examples of these are the deposits at Santa Rita, New Mexico, and Ajo, Arizona. The Arizona Mining and Trading Company produced high-grade copper ore at Ajo from 1854 through 1859.

Prospectors searching for gold and silver discovered other copper deposits in California, Utah, Nevada, Montana, New Mexico, and Arizona. In November, 1860, the initial discovery of copper ore was made in the Foothill Belt of California by a gold prospector. The outcrop contained gold and a mineral unknown to the prospector. An analysis showed that the ore contained 30 percent copper and was worth $120 per ton. "When this became know, local excitement broke out and soon spread to other parts of the Foothill Belt, hundreds of claims being staked and recorded."[62] The copper boom continued through the Civil War years. It has been estimated that by 1866 over 100,000 tons of copper ore, valued at over $5,000,000, had been taken out of California mines.

Until the railroads reached the copper districts, only the richest ores were mined. This is easily understood in light of a situation such as that which prevailed in the Clifton District of Arizona. Prior to the arrival of the railroad in 1881, copper bullion from the Longfellow Mine there had to be hauled in wagons for 700 miles to the nearest railroad terminus in Kansas.

5. Early Underground Mining Methods

The difficulties in mining base metals from hard rock in the 1800's were not solely the fault of inadequate transportation facilities. Before 1870, underground mining methods as practiced in the Western United States were scarcely one step removed from the mining methods of the Middle Ages. Drilling in hard rock was accomplished at first with steel or iron wedges, known as gads and moyles, driven home by hammers, which were of two kinds, the eight pound double-jack (if two men were used) and the four pound single-jack (if one man were drilling on his own). The drills came in progressive lengths, the longer ones being the thinnest, and were repeatedly sharpened by the mine blacksmith as they became dulled.

The accepted practice in tunneling was to begin by opening a "cut hole" in the center of the rock face and then drilling a set of three converging holes, about two feet long and aligned so as to meet at the top of a pyramid in the center of the face. The miner then loaded the drilled holes with cartridges of black powder and used a tamping bar to make the charge firm. The explosive charges were then detonated in proper sequence.

In the 1870's a great change occurred in both drilling and blasting. As early as 1849, a steam-driven rock drill had been patented in which the drill bit was an extension of the piston rod and was fed towards the rock as the drill advanced. Though widely used, it had never been completely successful because of the loss of power of the steam from the boiler, which of necessity had to be located at a considerable distance from the place where the drill was being used. About 1866 the patent rights were bought by Charles Burleigh whose great contribution was to make the drill work by compressed air.

From Burleigh's success flowed a whole range of rock drills that came in all shapes and sizes–Rand drills, Jeffrey drills, Ingersoll-Sergeant drills, and Holman-Climax drills. All of them were piston drills dealing from 300 to 600 blows a minute. They were very heavy and had to be bolted to a platform, but only two men were required to operate them. The revolutionary principle, by which air drove the piston and its attached drill forward, meant an immediate lightening of the physical load on the miner who was then compelled to display his prowess at hand drilling by organizing the competitive displays that were common in the early West.

The next marked improvement in drilling technology did not come until 1897, when George Leyner developed the hammer drill in Colorado. This was a much lighter drill, faster and more mobile, for its bit did not reciprocate with the piston but remained against the rock at the bottom of the hole, rebounding slightly at each blow. A modern hammer drill can deliver as many as 2,000 blows a minute.

Blasting underwent no less a revolution with the discovery of new explosives. The early miners were adept at working with black powder, a far cry from the days when they had split the rock by burning brush at the face and then shrinking it by dousing it with cold water. Conservative in their methods, the miners did not take kindly to Giant Powder, which had twice the detonating force of black powder, and complained in outraged fashion that the fumes made them sick. This was somewhat of an understatement considering the appalling hazards of both explosives, for all that stood between the miners and eternity was their own invented *squib* (fuse). This consisted of some black powder wrapped in several thicknesses of paper and then twisted to form a taper about three inches long. The burning end of the taper gave the blaster about 30 seconds to remove himself before the flame reached the powder train that led to the hole where the main charge had been inserted.

Neither black powder nor Giant Powder could last long, however, with the discovery of dynamite, which was to make blasting much safer. Alfred Nobel had made nitroglycerine in 1863, but found it unsuitable for mining and quarrying because of its instability, until he added sawdust absorbent. This new dynamite, the old nitroglycerine made safe, was to be of several kinds, all of which found favor in mine blasting, for their plastic nature made it possible to load the explosive solidly into drill holes, even though they were wet.

The main danger at first in working with the new dynamite underground came from the small copper detonators that carried a small charge of fulminate of mercury to set off the relatively inert dynamite. The procedure used in loading was to force home the end of the fuse into the detonator, crimp its neck with a special tool (which was never to be found, so the miner used his teeth), and then insert it into a hole which had been punched into the side of the stick of dynamite, binding the whole assembly firmly with a wrapping of coarse string. In time, miners were not allowed to do their own connecting of detonator to fuse and there followed stringent regulations for the separate storing of dynamite and detonating caps and requiring that they be carried separately in sacks down the shaft. Powder magazines also had to be modified to conform with the new safety requirements. Not only had they to be built far from all other buildings, but they had to be dry, well-ventilated, and bullet-proof.

Even what today seem to be simple innovations were major improvements in the mining technology of the 1860's in the American West. The underground mining methods previously in use had provided for the transporting of the ore from the working face to the shaft in sacks or baskets on the back of a man or burro and then on runners or sleds on wooden planks. After 1860 American mines saw two innovations, the Cornish wheelbarrow and the underground haulage railroad, both of which, for instance, revolutionized mining methods at New Almaden.

The wheelbarrow was of wood; it was long and narrow with no legs but with a bar of wood to allow it to rest on the ground; and it was designed with little inclination at the sides. It was thus well-equipped for working in confined spaces and much more convenient for tipping sideways than the conventional barrow with wide sloping sides and long legs. It was not long before the mine openings became lined with tracks of 18, 20, and 24 inch gauge, on which moved ore wagons, first of wood and then of boiler iron, capable of carrying a ton of ore at a time, and propelled by men or by animals. But the wagons still had to be loaded by hand from the wheelbarrow that carried out the ore from the working face until the invention of the mechanical scraper and gravity loading devices to increase the output of ore per man.

The broken ore, having reached the shaft, had then to be hoisted to the surface. The earliest method of raising the ore was the hand-operated windlass that had been in vogue in the shallow lead mines of Southwest Wisconsin in the 1840's. The came the *horse-winch*, a contrivance consisting of a circular drum around which a rope was wound and which was turned by a horse that moved in a circle. Another version was the Cornish *whipseyderry*, in which the horse moved in a vertical direction, and the Spanish-Mexican *malacate*. Water wheels were sometimes used, although the pressure of water was not always reliable. Water balances were also occasionally used for shafts not more than 600 feet deep. These were a kind of gravity conveyor, and they were still being advertised in the catalogues of manufacturers as late as 1897.

Before the appearance of the electric hoist, the most conspicuous advance in hoisting equipment was in the refinements of the steam-winding engine, first the Cornish beam engine and then the more efficient double cylinder horizontal engine. The winding engine was mounted on timber, a masonry foundation, or a massive cast-iron plate, and its boiler was of the locomotive type. Its drum could be either single or double and was bushed with gun metal. It was provided with safety catches to prevent the cages from running into the sheaves in cases of overwinding. Simultaneous with new winding devices went improvements in the making of ropes, hemp soon giving place to steel wire. In 1860, the firm that was producing the most-used cables in that West as A. A. Halliday and Company at North Beach, San Francisco, but by 1890 the market for mine hoist ropes was being served by a firm with a national reputation, John A. Roebling's Sons & Company of Trenton, New Jersey.

The ore produced in the West's early metal mines was first raised in iron buckets made of boiler plates, rivetted together and attached to chains, hempen, or wire ropes. These were of varying capacities ranging from 100 pounds to little more than a ton, but they were never to be used for really deep mining because of their propensity for swaying in the shaft, which had to be lined with heavy planks to take the buffeting. Their place was taken by *skips* which ran on guide rails and were pulled by wire ropes or by cages in pairs in vertical shafts, one ascending while the other descended, and each capable of carrying a car containing at least a ton of ore.

Conveying the ore from the shaft-head to the mill saw no special revolutionary changes, railroads being the usual medium. In localities where the contours of the country did not permit the building of railroads, however, there appeared a solution to the problem in the form of overhead tramways using wire rope. These were of two kinds: (1) the travelling rope system, based on the use of a wire rope travelling at a speed of about 350 feet per minute which, by its forward motion, carried the suspended load; and (2) the standing wire system

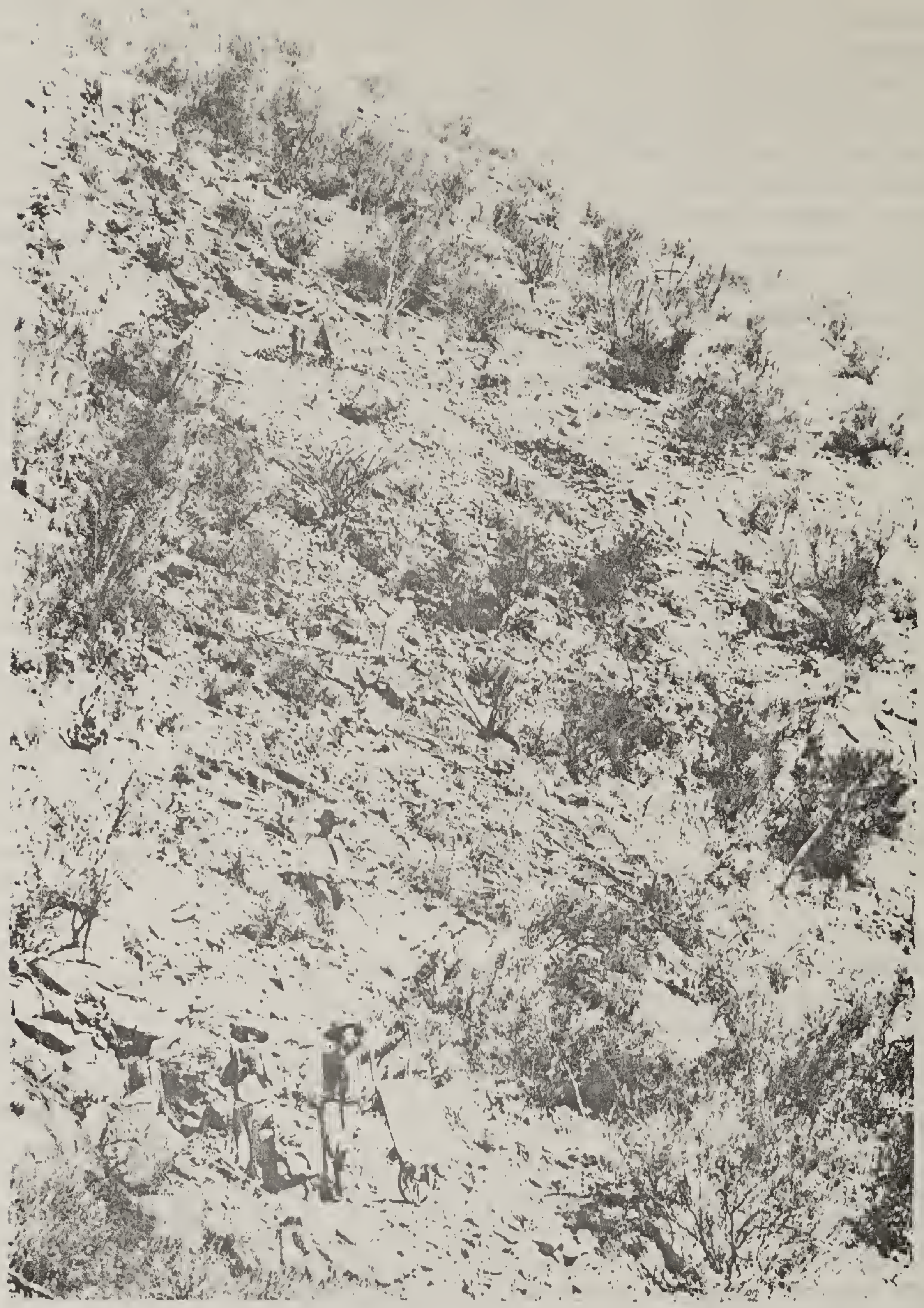


Fig. 30 - Materials handling in most mining operations prior to 1872 was rather primitive and limited to small amounts at any one time. The methods and equipment of materials handling limited the size of mining operations. (Photo courtesy of Arizona Pioneers' Historical Society)

in which the wire rope served as an overhead rail. The same methods were employed for transporting the waste rock away from the shaft. This was always a problem, particularly in flat land, since space had to be allowed for a dump, and, as the height of the dump increased, inclined tramways had to be built with a stationary engine at either the top or bottom of the incline.

6. Mining and the Environment

Environmental control has always been a matter of concern in underground mining. It is today, and it was no less so in the period prior to 1872. Of primary concern then were light, air, and water.

For a good deal of the period during the late 1800's, the sole source of lighting underground was the tallow candle, often being preferred even after the appearance of the carbide lamp and the portable electric lamp (about 1895), for the miner could not light his pipe with the latter. The candle, stuck in the hard hat with a ball of clay or on a holder so designed that it could hang from a hook or be driven into a piece of timber, was a familiar sight for many years until it was ousted by the small lamp that burned fish-oil. At the International Exhibition in London in July, 1874, there was exhibited a lamp that was illuminated by forcing air through benzoline. It could be used quite safely in main shafts and levels, but its acceptance was slow. The miner had other reasons for hanging onto his candle and it was to do with ventilation.

To the early miner, the burning of the candle was an indication of the degree to which a stope was well or badly ventilated. If it burned brightly, the air was fit to breathe, but if he had difficulty in keeping it alight when the air was still or if the flame became large and turned pale blue in color, then these were the indications of a decreasing supply of oxygen.

Ventilation could be either natural or induced, and in metal mines the former was usually considered more economical. Despite this there were a number of devices to assist natural ventilation. The *air sollar* was a device designed to produce a natural current of air in a long level. To form an air sollar, the floor carrying the haulage track was laid about six inches above the actual rock bottom of the level and supported by cross-ties resting upon blocks of wood or stones. Planks were laid over the sleepers or ties to form a kind of deck, and the whole was made airtight by plastering it with mud or clay. This arrangement thus divided the level into two very unequal portions. Through the lower space which was the air sollar, a current of cool (and heavier) air would pass into the end and would be further cooled by any water that happened to be issuing from the rock. The hot air rising from the breathing of the men and even from their candles passed out through the upper portion of the level. This simple system of natural ventilation was still being used with effect at Bisbee, Arizona, in 1912, although it was then modified by small centrifugal blowers driven by electric motors.

Pipe and cap-head ventilating in underground mines was similar to that used on ships. A pipe of thin metal or wood, about one square foot in area, was installed in the shaft and fitted at the top with a revolving cap-head. The lower end of the pipe at the bottom of the shaft was open. The open mouth of the cap-head at the surface was left free to be turned in the direction of the wind. Thus a current of fresh air could be forced down the shaft and the foul air made to ascend. This method also was used for ventilating levels, provided no really sharp bends were made in the pipe. Its weakness, of course, was that it could work only when a strong wind was blowing, and miners needed ventilation most when the air was still. To overcome this difficulty, a small fan was often placed at the upper end of the pipe, worked by hand, water-wheels, or a steam engine.

The *water trompe* was a device used with considerable advantage if there was an ample supply of water at the surface and an adit level to drain away the waste water. This device consisted of a very simple arrangement in which water from a launder fell upon a series of iron bars set in a pipe and then down the pipe into a sump. The stream of water carried a quantity of air down with it, which escaped from an exit pipe at the bottom of the shaft and so into the level.

Natural ventilation, however, was best achieved in early underground mines not so much by these contrivances as by the position and depths of the shafts (where deposits were worked to a moderate depth) so that the air would flow naturally down one shaft, through the drifts and up another. The working of a deposit in mountainous country with entry by both adits and shafts could also provide a chimney draft effect and substantial natural ventilation.

But as the mines became deeper and hotter, as in the Comstock, such methods were quite inadequate to provide sufficient ventilation, especially when the law required that a stated quantity of fresh air per minute should be available for every man and animal. On the Comstock a miner might lose as much as six and a half pounds of water every hour through sweating and become completely depleted of salt. Drinking water to excess only led to cramps. Today, special thermometers can measure the cooling effects of refrigerated fresh air in millicalories per square centimeter per second, and salt tablets can assist the miner, but in the 1860's no such aids were available. Even sprinkling dusty stopes with water was of little effect against the heat from hot wall rock, from men, machinery, and lights, from blasting, and from the oxidation of pyrites.

In no aspect of early mining was there so much experimentation and innovation as in that of ventilation, as engineers and miners alike searched for solutions to the problems of controlling and directing underground air currents by regulator doors and various types of devices. But probably the most important contribution of technology in solving the problems of mine ventilation was the air-compressor, although such was not its purpose. In 1878 an hydraulic air-compressor was developed for work at the Victoria Mine in Michigan, and from it flowed a whole technology and discipline regarding the care and maintenance of compressors and drilling machines, the correct placing of air-pipes in shafts, and how best to hang air lines to prevent leaks and still provide access to them. Compressed air became the key to many problems, both intentionally and unintentionally. It drove rock drills, locomotives, pumps, hoists, and loading machines; it sprayed water to keep down dust; it operated ore gates and waste bins; it opened and closed mine doors; and its air lines could be used as water lines in case of fire. And the miners quickly found it could be used as a source of fresh air.

7. Water and Mining

There have been few mines, surface or underground, that have been completely free of some accumulations of water, and it has been an ancient practice to take care of this problem to some extent by the driving of adits beneath the mine workings to drain off the water by gravity on the rather sensible grounds that the more water that is gotten rid of in this way, the less costly is the work of pumps. In the history of the world's mining, there have been some very complicated drainage adits driven. One at Gwennap in Cornwall, begun in 1770, drained about 30 square miles with a system of branches that extended a distance of more than 40 miles. By 1880 this system had merged into the Great County Adit which was more than 100 miles long. The Ernst August Adit in Saxony drained the mines in the Harz Mountains, was 14 miles long, and took 13 years to drive. Part of it was navigable by boats. In the early days of the American West there was the Sutro Tunnel in Nevada, 22,000 feet long, and the Snake Creek Tunnel in Utah with a length of 14,000 feet.

In the first American mines, that is, in the ones that were shallow enough, water was raised by hand or by a windlass in skins or buckets. As the mines became deeper, however, more sophisticated methods had to be adopted. After 1860, undoubtedly the most important contribution to mine drainage was the Cornish pumping-engine. Although it was in its heyday when it became the vehicle for draining the Western American mines, behind this steam engine of massive proportions stood a century of Cornish techniques in the actual business of mine draining.

The pump was, strictly speaking, the tubes into which the water was drawn from the sump, the central point in the mine where the water was collected from various points by gravity. The general design of the Cornish pump was based on raising the water by a series of lifts, so sumps were built into the sides of the mine shaft and supported on strong beams. They were usually made of wood and strongly bound with iron strapping. Special precautions were taken if it was known that the pumps would be raising water from acid ground, for then the working parts would be made of gun-metal and the pumps themselves lined with staves of oak.

The principle on which the machine worked was very much that of the ordinary household pump of years gone by. With the "up" stroke of the engine, the water was raised, forced up by the weight of the main rod or rods. A balance had to be maintained between the weight of the rods and the weight of the water. At times these rods were of an incredible length and weight, sometimes as much as one-third of a mile and weighing 100 tons, in which case their weight would be more than enough to raise the water. The surplus weight would then have to be counter-balanced by "balance-bobs," placed either at the surface or in chambers excavated in the side of the mine shaft. The business of joining the sections of the main pump rod was always something of an artistic achievement, especially when the mine shafts were not only deep but steeply or irregularly inclined. The usual method was to try to get the main rods to go round corners, but in one Grass Valley, California, mine this proved so difficult that a carpenter had to be imported especially from Cornwall.

There can be no doubt that the Cornish pumping engine proved itself superior to any other form of draining mines in the age of steam. These machines could raise as much as 2,000 gallons of water a minute and could work, with proper care and maintenance, almost indefinitely. Four in the Severn Tunnel in England worked from 1879 until 1966 continuously, pumping out nearly one million gallons of water a day, and only their bearings had to be replaced. Very few of the Cornish pumps have survived, however—a handful in Cornwall and hardly any in America. One of the most famous was at the Buena Vista Shaft at New Almaden and another was at the Chapin Mine near Iron Mountain, Michigan. Both were regarded as the mechanical wonders of their day. The Chapin engine's bob weighed 120 tons and its flywheel 160 tons, revolving on a shaft 27 feet in diameter. With both a high- and low-pressure cylinder, and costing $250,000 when new, it could lift 200 tons of water a minute from a depth of 1,500 feet, equal to 4,000,000 gallons a day. Today, it has been removed to a nearby site and preserved for its historic interest.

The Cornish pump was never really ousted until the arrival in the 1900's of the electric pump which gave greater efficiency in much less space. The direct-acting pumps that made their appearance in the late 1870's likewise constituted a threat to the supremacy of the Cornish pump. In these the pumping engine was placed at the bottom of the mine shaft and was supplied with steam by a clothed steam pipe from a boiler on the surface. The piston rod had a piston at one end and a ram at the other. The piston worked in the steam cylinder, and the ram was a force pump or water cylinder which communicated with the pump. Its serious drawback was that it could easily be lost by sudden flooding and so duplicate pumps had to be installed, thereby adding to the costs of mine water removal.

In virtually all American mines of any consequential depth before 1872, excess water was a problem. The biggest part of the problem then lay in removing it from the mine, not in disposing of it once it reached the surface. In most instances it was either turned into the natural surface drainage system or used in ore beneficiation or both.

8. Early Beneficiation Methods

In the middle and late 1800's there was in most places relatively little distinction between the beneficiation and advanced processing phases of mineral production. The complex chemical processes of the 20th Century had not yet been developed while most of the methods then used for recovering metals from their ores had been known for centuries. The Hoovers, in their translation of the classic *De Re Metallica* by Agricola, listed many of the oldest ore treatment processes, and a selection of these is listed in Table 25. Some of these are what are now considered strictly beneficiation operations while others involve more advanced processing. Beneficiation is here taken to include the physical processes by which the crude ore was finally converted into relatively pure ore minerals or metallic compounds. It involved both ore dressing and the process of concentrating. If the advanced metallurgical process were one in which the recovery of the metal from the concentrates was effected in a melt, it was called smelting; if by some aqueous or other solution, it was called leaching or lixivation; and if by vaporization and subsequent distillation, it was called retorting.

In the Western United States before 1860 there was only the Spanish-Mexican tradition as a guide to the reducing and concentrating of gold and silver ores, and even these had to be exceedingly rich before the Mexicans would bother to deal with them. Crushing at first entailed hardly more than exposing the ore to the air and pulverizing it with hammers and sledges. After roasting and calcining to break up the gangue and to expel the arsenides or sulfides, the ore was introduced to a grinder, of which there were three varieties.

The *Korean Mill* was the most primitive of all grinding devices used in the early West and had been widely used in China and throughout Asia. The Mexican version was a boulder rotating in a stone, the gyratory motion being produced by two men see-sawing up and down on the boulder and thus crushing the rock inside. The *Arrastra* was a more sophisticated affair and had its origins in the days of the Roman Empire. It consisted of a circular stone floor, sometimes level and often slightly inclined to the horizontal. Surrounding it was a low coping of stone, in the center of which stood a wooden or stone post which also served as a pivot. Projecting from this pivot were sundry poles to which were attached raw-hide ropes bound securely around drag stones. These stones weighed about 200 pounds each and were bevelled at their lower edge. Motive power was provided by a mule or horse attached to the pivot. The walking animal turned the pivot, and the pivot moved the drag stones.

The grinding procedure thus developed involved filling the *arrastra* with broken ore and some water. As the horse or mule made its circular turns, the large stones bit into the ore with a gyratory and abrasive action, in time grinding it to a pulp or slime, which was then allowed to drip through a screen, from which it was taken for further treatment by mercury. It was really a functional wet grinder, the forerunner of the rod and ball mills of a later time. The *arrastra* had a long history behind it in 1860 and still had much useful work to perform, for it was relatively mobile, easily made from local stone, and sound in its principles. In the late 19th Century, manufacturers in the West were producing them in bulk.

The *Chilean mill* was superior to the Mexican *arrastra* and could be operated by water power. It consisted of the usual stone floor and coping, but instead of the drag stones, it had two large stone wheels, set on edge and rotating on a pole-axle which revolved about a central pivot. It was a skilled matter to cut, shape, and set the wheels, however, and this added to the cost of the Chilean mill. Nevertheless, by the end of the 19th Century it was being manufactured in several sophisticated forms for use in the beneficiation plants of the West.

While the Korean mill, the Chilean mill, and the Mexican *arrastra* were all used to grind already broken ore, at most hard rock properties in the West before 1872 it was first necessary to crush the ore as it came from the mine. *Stamps* were one of the most important instruments for crushing. They consisted of a series of heavy treadles or feet, shod with iron or steel and arranged in batteries, lifted by cams keyed onto a revolving horizontal shaft. Steam stamps were used in a limited way in the native-copper mills of the Lake Superior district in Michigan, taking the place of the earlier gravity stamps. The latter had been in use for reducing tin ores in Cornwall since the 18th Century and were found to be ideal for preparing gold and silver ores for amalgamation. One of the first of these was used in California in the early 1850's. In time the transfer of technology reversed itself and California stamps, with greater speed and dropping capacity, found their way to mills in Cornwall. With the introduction of the cyanide process for gold recovery, however, finer grinding became necessary and stamps were relegated to the position of intermediate crushers.

The crushing and grinding methods used for hard rock ores, for the most part had not been necessary in the working of the early placer deposits. Nature had already reduced the

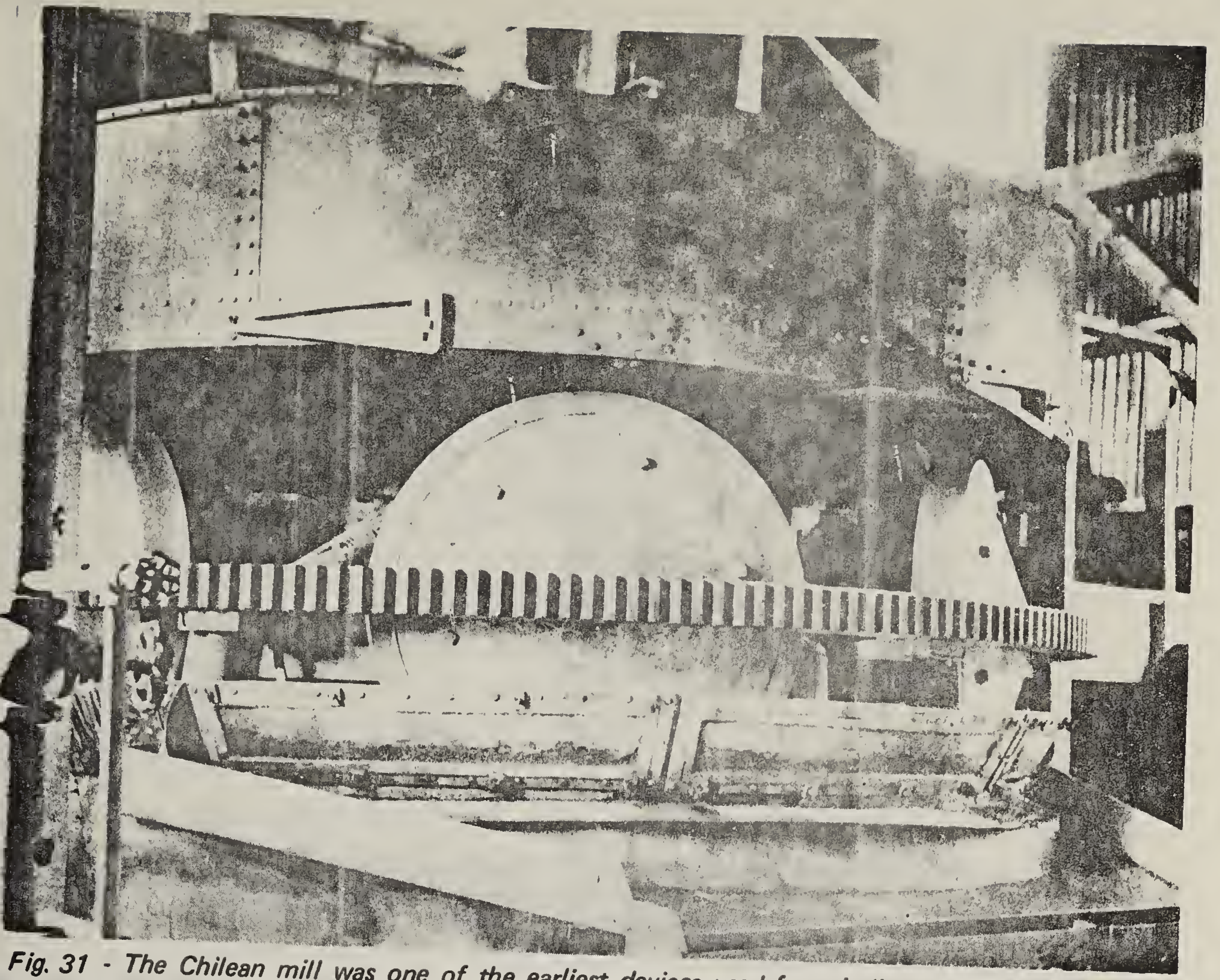


Fig. 31 - The Chilean mill was one of the earliest devices used for grinding gold-bearing ores in the Western United States. Similar methods involving the even more primitive Korean mill and the Mexican arrastra were also used before 1872. These were small capacity devices that required relatively little space but considerable man or animal power. Above is a highly mechanized version of the Chilean mill that was developed about 1900. (Photo courtesy of Arizona Pioneers' Historical Society)

particle size of the rock in these deposits and so the primary problem became one of separating the valuable from the valueless. Most of the concentration processes used water, but in many parts of the West, water was even scarcer in 1850 than it is today. *Bed-sheet drywashing* was a concentrating operation used when there was little water available. In this crude method a shovelful of dried sand was thrown on a sheet or blanket and the wind allowed to blow away the "chaff" in hope that a particle of gold would be left behind. If there was no wind, the miner did his own blowing. The method was not very effective, for much of the gold was lost, blowing produced spots before the eyes, and the whole procedure was tiresome. Yet it was never completely abandoned.

The most commonly used early method of beneficiating placer gold ores was, of course, *panning*, the same process used by the prospectors in their search for gold anomalies. In panning, a pan of gravel was placed in water and stirred by hand to break up the clay, the large stones were picked out and the pan given a circular movement to settle the heavier particles. During this process, the pan was tilted from time to time to wash off the surface layers of lighter material. Finally, with luck, a little black sand would be left in the pan with some gold, which could then be collected by adding mercury. The rate of progress achieved might be one cubic yard of gravel washed in ten hours.

The first pans were probably tightly-woven Indian baskets, but soon two types of metal pans made their appearance in the California placers. One was the Spanish *batea,* a flattened conical affair ranging from 16 to 30 inches in diameter. Then there was the American

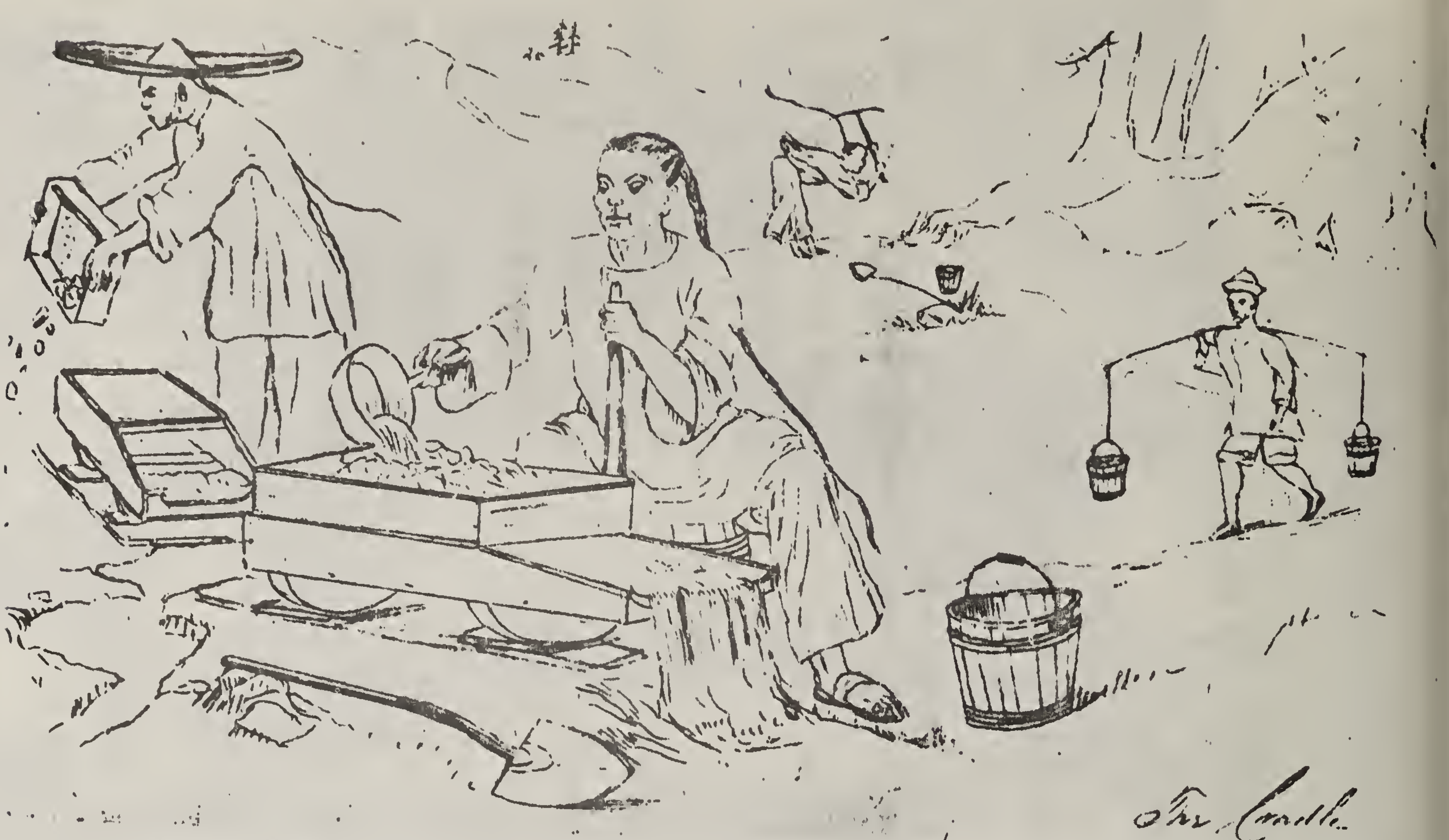


Fig. 32 - Miners using the cradle pan to beneficiate gold-bearing gravels from the American River in California in 1863. Such gravity concentration equipment was really little more than a modification of the ancient miner's pan. Its use involved only a comparatively small area but required an abundant supply of water and manpower. (Photo courtesy of Arizona Pioneers' Historical Society)

circular, flat-bottomed, iron (and later steel) dish 18 inches in diameter and four inches deep, with outward-slanting sides set at 30 or 40 degrees to the horizontal and sometimes with handles. The latter originated in Alabama and Georgia, where placer mining for gold had started as early as 1830 and where one Isaac Humphreys is credited with the design of the American pan for the low-yield placers.

The American style pan became dominant though there is evidence to suggest that the *batea* lent itself more to mechanization than did the American pan. The nearest the American miner came to mechanizing his pan was to convert it into a large wooden bowl and put it on rockers like a child's cradle, thus permitting him to stand upright and straighten his aching back, while he rocked the pan with one foot. But this first mechanization was to be the beginning of a whole series of inventions designed to speed up the work and yield economies in both time and effort as long as the alluvial deposits were worked.

The rocker or cradle pan soon went through several refinements so that two men were required to work it. The more elaborate version consisted of a tilted wooden trough about 20 inches wide and 40 inches long, with sides about four inches high. The lower end was left open and the whole contraption was supported on two rockers. On the upper end was a hopper approximately 20 inches square with wooden sides. On the bottom of the hopper was a length of sheet-iron or zinc, pierced with holes about half an inch in diameter. Under the hopper was an apron of wood or cloth which sloped downwards from the upper end of the cradle box to the lower end of the hopper. A strip of wood one inch square, called a riffle bar, was nailed across the cradle box. The intention was that the gold and the heavier particles should be caught behind the riffle bars and then the gold itself would be caught by mercury. But much trouble was caused by the packing of dirt behind the riffle while much of the amalgam was lost.

The *puddling box* was like the rocker but was designed to dissolve the tough auriferous clay. It consisted of a rough wooden box one foot deep and five feet square. The gold-bearing clay was thrown in with water and worked about with a hoe until it dissolved, the thinner and lighter mud then running away through a hole, leaving the heavier material at the bottom. At night, after the day's puddling, the concentrates remaining in the box were washed out with a pan or cradle. The *long tom* was really an extension and elaboration of both the cradle and the puddling box. It was also a wooden trough, but much longer, up to 14 feet in length and eight inches deep, with the usual hopper of perforated zinc and riffle bars. While effective at first, hardly any of these devices were to be seen in California after 1860.

The board sluice was to be by far the most important invention (prior to 1872) for the washing of gold-bearing dirt. It consisted of a large wooden trough, varying from one foot to five feet in width, and from 50 to 1,500 feet in length, and the longer it was, the more efficient it became. It was usually set at an inclination of one inch to the foot, but the larger the apparatus was, the steeper the inclination and the greater volume of water required. The board sluice was constructed of one and a half inch thick boards, about 12 or 14 feet long, and in sections of that length, so that it could be added to, easily assembled, and easily dismantled. The boxes or compartments stood on trestles and could be used by different groups of workers, thus allowing for a vast amount of dirt to be washed. A constant stream of water entered the head of the sluice and ran the entire length of the boxes. At the bottom of the sluice were longitudinal riffle bars, two in each box, measuring six feet in length, two to four inches in width, and three to seven inches in height. Two hours after washing was begun, mercury was inserted into the top of of the sluice and allowed to gradually work its way downwards, collecting the gold that lay before it. The whole sluicing operation, called a "run," usually lasted six days with the Sabbath, the day of rest, occupied with cleaning out the boxes and sharing the spoils among the working gang of 15 to 20 men.

The *rock sluice* was virtually the same as the board sluice but it had a cobblestone bottom instead of the wooden riffles and required a steeper grade, a larger body of water, and a wider cross-section. The idea behind it was to get the sluice box to behave as nearly as possible like the natural action of a steam. Stones were lapped over each other in natural layers, inclining downstream, and fixed in position by nailing strips of wood over them. In this way it was claimed that 20 percent more gold could be saved, while thieves found it more difficult to rifle the riffles.

Of all the innovations found in early placer ore beneficiation, by far the most important was the sluice box itself, for it was an integral part of the next stage of placer mining (hydraulicing) and was an item of equipment that could be ordered in bulk from manufacturers. Even the later dredges used what was really only a modification of the sluice box to wash the enormous volumes of sand and gravel that they handled.

9. Advanced Processing Methods

But placer gold ores quickly gave way to hard rock ores of not only gold, but silver, copper, and lead as well. All of these required more advanced methods of treatment than washing and amalgamation. Nearly all of the occurrences of other metals were as compounds, not as native elements, and as such they needed reduction by smelting as well as crushing, grinding, and concentration. All the gear and apparatus for reducing and concentrating ores were centered in the *mills*, from which the concentrates were sent to smelters for final metallurgical processing. There arose specific provisions in the early mining laws regarding the location of the mills. The five-acre millsite claim was a direct outgrowth of the size and nature of the early beneficiation plants. Smelters, as such, were not subject to the same laws. They could be built on the mining site or at some considerable distance, depending on the fuel available and the nature of the concentrates to be refined and whether they were to serve one or several mines. In the latter case, like some of the mills, they were called "custom" smelters to distinguish them from integrated smelters.

In the early days in California, Nevada, Montana, Colorado, and Arizona, some metallic mineral producers, faced with refractory ores that they could not master, sent them as far away as Swansea, Wales, for smelting. The *Mining and Scientific Press* of August 3, 1861, was reluctant to accept this practice. Describing the Pacific Metallurgical Works in San Francisco, where ore was reduced in Chilean mills and then concentrated in special rooms, the *Press* commented, "With these metallurgical works so complete it is downright folly to send ores to Europe for reduction." The installation of metallurgical plants in the West, growing mine production, growing domestic demand for metals, and the development of new processes for metal recovery from the western ores soon made shipments to Swansea a thing of the past.

Gold, of course, was the West's principal mineral product in the 1850's and 1860's, and amalgamation with quicksilver was the principal means of recovering the metal from its concentrates. Even in the decades prior to 1872, there was such a profusion of amalgamators on the market that extensive advertising for them in the western newspapers was common. In 1860 the Knox Patent Amalgamator was being manufactured in San Francisco and was being used with effect, an advertisement claimed, in the mill of the Merced Falls Mining Company on the Merced River near Hornitas in Mariposa County. Many other varieties were being produced in the same year by foundries in St. Louis and Chicago to cope with the rush to the diggings near Pike's Peak. These were described as consisting of two iron rollers, arranged and worked after the manner of the *arrastra* which, revolving, pulverized the quartz ore and threw the mineral upon the quicksilver on the plate in the center, "where it is easily collected." In 1861, one Dr. J.B. Beers of San Francisco contended that he had invented an improved amalgamator that would effect a saving of as much as 25 percent of the gold by a series of amalgamating pans arranged in tiers one above the other.

The life blood of the amalgamation process was quicksilver and it thus became desirable to produce quicksilver as efficiently as possible from its native western ores, assuring an ample local supply. Mercury, as has been mentioned, had been produced on a very small scale in California even before the Gold Rush of 1848-49, and accessible deposits of the amalgam ingredient were already developed.

Cinnabar, a sulfide of mercury, is the principal ore of quicksilver, and the separation of the metal from the associated sulfur was effected by retorting, that is by roasting the ore in kilns and then condensing the mercurial fumes. At the New Almaden mines in the 1890's, the complete process of prospecting, development, extraction, reduction, concentration, and retorting could be seen on the same site. The ore was brought from the mines to the reduction works in cars run by gravity pulleys and then dumped into shutes, where screens separated it into three sizes, *granza,* the coarse ore, *granzita,* the medium ore, and *tierras,* the fine ore. Thirty years earlier, in 1860, these fine ores had been mixed with clay and water and made into bricks called adobes and dried in the sun. The coarse ore and these adobes were then piled into the roasting chamber, which held about five tons.

The distilling apparatus was a kind of reverberatory furnace, three feet by five feet, arranged at the end of a series of chambers of nearly the same size, seven feet long by four feet wide and five feet high. There were eight or ten of these chambers in each series, built of brick, plastered inside and secured by iron rods, strengthened at the ends with screens and nuts as a protection against expansion by the heat. The tops were of boiler iron. The first chamber was for a wood fire and the second chamber was the ore chamber. The two chambers were separated from each other by a screen of brick arranged in a lattice-work pattern. The flames from the fire passed through the square holes in the partition and licked the ore and bricks in the ore chamber. Next to the ore chamber was a series of condensing chambers, connected to each other by square holes. The vapors and smoke passed from the ore chamber, through the condensing chambers and then through a square wooden box, eight or ten feet long, in which there was a continuous shower of cold water. The smoke escaped into the open air through tall wooden flues.

The retorting process lasted about 60 hours and the main principles never changed, the only modifications being in the size of the furnaces, automatic devices, and the installation of fans in order to reduce the incidence of salivation in the retort workers brought on by the inhaling of mercury fumes. Not until the appearance of Guibal fans in 1881, however, and their operation by electric motors seven years later, could it be reasonably said that salivation (spitting oneself to death) had been brought under control.

While mercury's primary use in the West before 1872 was in the recovery of gold, it was also used to a certain extent in the recovery of silver. With the growing importance of silver production after 1859, mercury recovery became even more important.

The extraction of silver from its ores or from ores in which silver was combined with other metals was, in the last half of the 19th Century, effected by three main processes: (1) *amalgamation,* in which the silver was caught by mercury; (2) *smelting,* in which the silver was caught in a lead or copper bath; and (3) *lixivation,* by which the silver was won in an alkaline solution. In 1860 two well-tried processes involving amalgamation were readily available in the West. These were the Mexican *patio process,* which dated back to the 16th Century (variations of which were the Chilean *cazo* and the Bolivian *fondo*), and the *European* or *Freiberg process.*

In the patio process, the ore was first picked over by hand and then roasted to remove any excess of sulfur, after which it was pulverized in crushers, stamps, Chilean mills, or rolls. The crushed ore then went to the *arrastra* for grinding with a mixture of water and mercury in preparation for the patio. This was a large court with a paved and slightly inclined floor on which the pulp from the *arrastra* was spread to dry to a thick muddy consistency. It was then piled into what was called a *torta* of about 150 tons at a time, spread out into a bed about ten inches thick. Salt was scattered over it and the mixing achieved by mules treading it, a procedure which apparently even by 1900 had not been superceded by any form of machinery.

The *magistral* was then added. This was an uncertain quantity of a hot solution of copper and iron sulfates and oxides that was determined more by instinct and experience than measurement. Then the mercury was added, in showers (by squeezing it through canvas bags) and at regular intervals, the whole being treaded in again by mules. The chemical reaction that followed took the form of the mercury working on the copper chloride to form sub-chlorides of both. The copper chloride absorbed the oxygen, which then acted on the silver sulfide and made sulfuric acid, leaving the silver in a metallic state to be absorbed by the mercury and then recovered by retorting.

Admittedly the patio process was wasteful and the loss of mercury was fantastic, but it was still relatively cheap and required virtually no capital other than the cost of mules. Moreover, it was ideally adapted to hot and dry climates where little fuel and water were available. Because of these factors, the process persisted well into the present century until superceded by electrolytic methods.

San Francisco's *Mining and Scientific Press* of April 6, 1861, quoted the *Marysville* (California) *Democrat* describing a "new silver process at Washoe." In the *Washoe process,* the rock was selected at the mine with only the richest ore being taken to the mill, where it was dried in a kiln. Then the dried ore was stamped and reduced in a dry state to powder, passing through a fine sieve. The powder then fell into a long box, having in its bottom a spiral scraper, which conveyed it to a set of elevators. The elevator deposited it in the "bolting wheel," where the very finest material was separated from the coarser particles (the latter falling through a spout) and returned to the stamp batteries for further stamping. From the *bolting room,* the ore was taken, weighed, and mixed with ground salt in preparation for the *Freiberg process.*

Amalgamation, whether by the patio or Washoe (Freiberg) process, could only be used with certain ores. But at many Western mines concentration had to be undertaken because the ore was too low-grade to justify even preliminary roasting and was not rich enough to amalgamate raw. This proved to be the case in the brief life of the Calico district in California. There the *Boss process* was used because the Calico pulps could be worked very thin. They were fed through five amalgamating pans, the chloride ores yielding about 95 percent of their assay value and with as much as 95 percent of the amalgam being recovered.

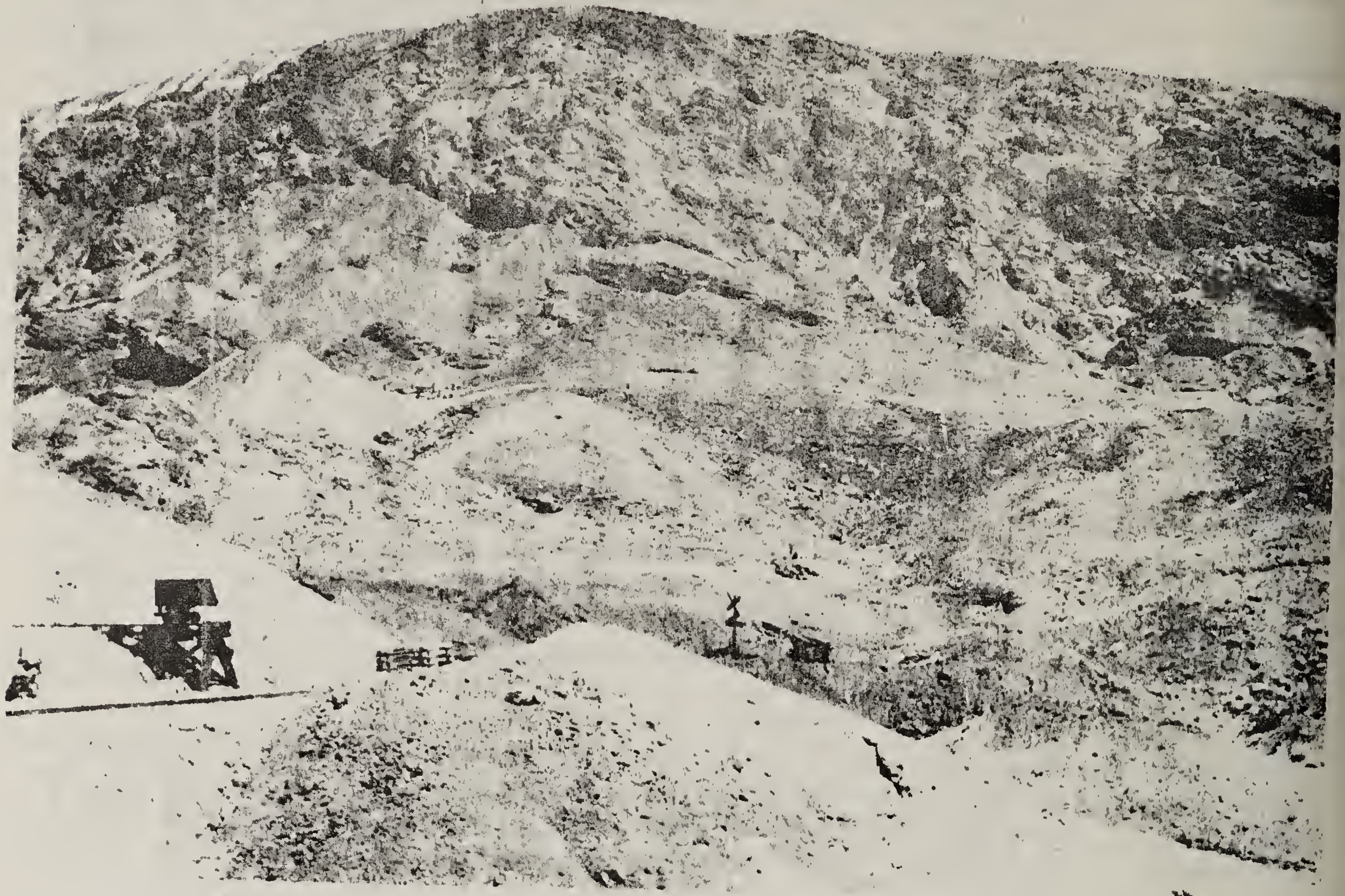


Fig. 33 - Waste dumps at Calico, California, where early silver miners used amalgamation to recover silver from roughly concentrated silver chloride ores. The limitations of 19th Century technology and economic conditions restricted the working of these and similar deposits to only high-grade rock and selected ore minerals.

Smelting had to be used if the silver was accompanied in the ore by much lead or copper, and this was the case with the majority of the western ores. In the Tombstone district of Arizona (in the 1880's), concentration was achieved by various gravity devices, and then the concentrates were made into bricks by binding them with slimes. The flux used in the smelting was manganese ore and proved to be most successful.

In the lixivation of silver, five processes were used during the period before 1872. The *Augustine process* was mostly employed on copper mattes by roasting the ore to drive off the sulfur, grinding the roasted ore, then roasting it with salt to form chlorides, dissolving the chlorides with a saturated solution of salt, precipitating the silver with copper and finally compressing and melting the silver. The *Ziervogel process* began by roasting the matte to produce sulfates and then went on to decompose all the sulfates except that of silver, finally dissolving out the silver sulfates in hot water. The *Voor Patera* and *Kiss* methods were about the same, using roasting to drive off the sulfur, leaching with hot water to remove soluble salts, roasting with salt, dissolving the chlorides by sodium hyposulfite, precipitating the silver by sodium polysulfide, and then reducing the silver sulfide. But the method that had the widest application and the most successful results, tried and tested in the 1860's, was the *Russel*, for it proved that it could hold its own both economically and metallurgically with amalgamation of free-milling ores.

10. Production Costs

Despite the enormous amount of hand labor involved in minerals production prior to 1872, the costs of such production were relatively low by present standards. The reason, of course, is that labor was paid far less than now. In most of the mining districts of the West, miners were paid between $3.50 and $4.50 per day and the day lasted from ten to 12 hours. Skilled smelter workers were paid slightly more. Common labor received much less. In Northern Idaho, for example, woodchoppers and charcoal burners were paid between $65 and $75 per month plus board in 1872. In most cases this averaged less than $3.00 per day.[63]

As might be expected, mining and other production costs varied from one region to another. In most of the California gold districts in the 1860's, mining costs alone averaged about $2.50 per ton. In Nevada and other parts of the West, costs were normally higher. On the Comstock, costs ran about $4.00 per ton of ore mined, while in some more remote areas mining costs were occasionally as high as $10.00 per ton.

Beneficiation and advanced processing costs were extremely variable, depending not only upon location alone but upon the nature of the ores and the processes used in recovery of their metallic content. At Grass Valley, California, in the 1860's, total milling costs for hard rock gold ore amounted to a little more than $2.00 per ton treated.[64] In some other districts, beneficiation costs were as low as 50 cents per ton. Smelting costs averaged between $3.00 and $10.00 per ton treated.

Although the nominal value of the contained metal in a ton of ore was normally much higher than today (ranging from 15¢ per ton in some of the low-grade gold placers to over $200 per ton for some of the better lead-silver ores), the difference between mining and treatment costs and the price of the recovered product was not all profit for the producer. Extremely high fees were paid to transportation companies, and shipping was in most cases by far the largest single item in the cost of delivered mineral commodities. From some Arizona mines in the 1860's, freight charges to reduction works in San Francisco exceeded $25 per ton for ore that took only $10 per ton to mine and mill. At the Vulture Mine near Wickenburg, one of the few gold mines in the Southwest at that time, the hauling of ore from the mine to the mill (a distance of 14 miles) cost $8.00 per ton. At the same time, some properties in Nevada were paying freight charges of $80 per ton, and a few mines in more remote areas had to pay as much as $140 per ton to ship their ore.[65]

C. CHANGES IN MINERAL PRODUCTION TO 1947

1. Changes in Mining Methods

Undoubtedly the most significant change in the mining industry of the Western United States from 1872 to 1947 was the general shift away from the precious metals and high unit-value minerals to the production of base metals and lower unit-value industrial minerals. Improved transportation was a major factor in the tremendous expansion of western mining in the almost eight decades between 1872 and the end of World War II. A network of railroads, giving access to base-metal districts whose economic success depended on rail haulage, was virtually complete by 1947. A corresponding network of paved highways had grown rapidly since the 1930's. Trucks had replaced the oxcart, and air travel was expanding. Electric power had replaced steam power, and numerous other technological innovations had been introduced.

Mechanization in mining increased substantially towards the end of the 19th Century and took many forms. Mine cars used for hauling ore both underground and in surface pits were of several types. The solid or box type ore car required a rotary dump at the loading point while the rocker dump type (with a V-shaped body rounded at the bottom), the gable bottom (shaped like a capital W in cross-section), the Granby car (which was a side dumper), bottom dump cars, and end dump cars all required less elaborate auxiliary equipment.

Loading machines came on the market in the late 1800's, driven by compressed air or electricity. They were generally of two sizes, the power shovel that could work in large drifts, and a smaller and lighter loader for working in small openings. Also introduced were car-loading slides, useful in the mining of flat deposits where vertical raises were not needed and in driving drifts, cross-cuts, and tunnels.

Self-acting endless chains or conveyor belts were in use as early as 1895, but the most important innovation in hauling ore from stope to shaft was the use of locomotives. Electric traction had proved to be the best of all in surface, non-mining applications and was coming into its own about 1896 in mining as well. The underground trolley locomotive, taking its power from overhead wires, became used for the heaviest work, while the locomotive working off batteries that required no wires could work in all kinds of difficult places. Compressed air locomotives also had their advocates and in many cases were no less efficient than the electric ones.

Mechanization also played an important role in the auxiliary operations of mining, particularly in those concerned with environmental control and waste management. The availability of electric power where needed in the mine was a major contributing factor in the changes that took place in these operations. In the handling of excess water, various makes of electric pumps were introduced the 1890's and early 1900's. These new pumps had tremendous capacities and great mobility. A three-throw Cameron could raise 8,400 gallons per hour to a height of 4,800 feet, and one of the first electric turbine pumps in 1911 unwatered the Columbus Consolidated mine at Alta, Utah. But the appearance of electric pumps also marked the inevitable replacement of the Cornish pumping engine, for the reciprocating rods or spears of the Cornish pump were replaced by fixed pipes carrying a column of water which, when acted upon by the impellers of the turbine, caused the water to be forced to the surface.

The devices introduced for improving mine ventilation were legion, as the *Engineering and Mining Journal* demonstrated when, in 1912, it published the *Handbook of Mining Details*, which consisted of a series of articles on mine atmosphere control published in the previous ten years. Early instances were noted of prospectors who would build a fire at one side of the bottom of a shaft, a method that was especially effective in a two-compartment shaft and even more so if it were improved by a small sheet-iron stove with a long chimney to the surface. Even sails had been known to have been erected to deflect the wind down a sheet-iron pipe to the bottom of a shaft.

With another method, ventilation could be improved by a system of hydraulic air-blasts,

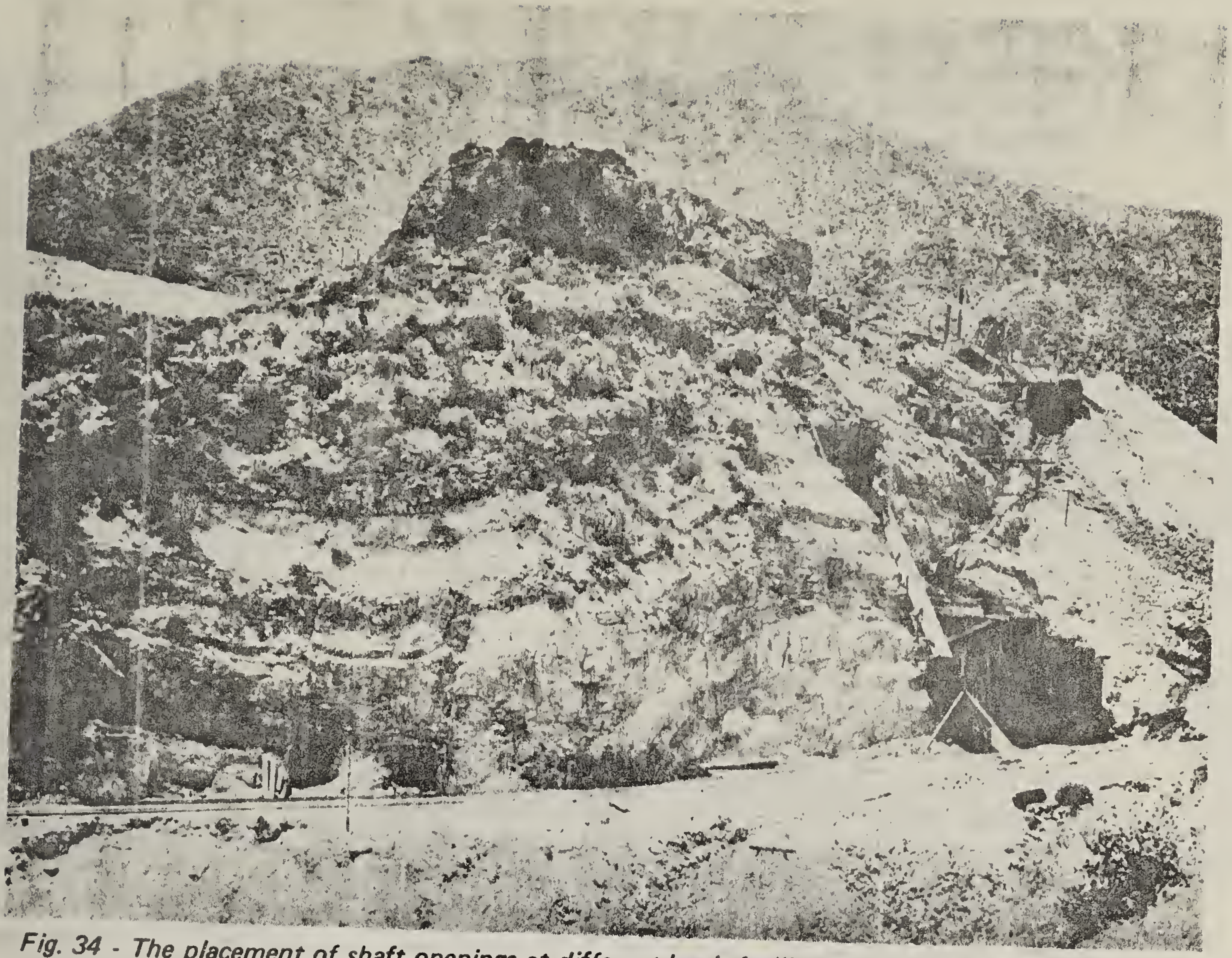


Fig. 34 - The placement of shaft openings at different levels facilitated underground ventilation before the installation of induced ventilation systems became common. Such placement was also quite often dictated by the terrain in which economic mineral deposits were found. (Photo courtesy of Arizona Pioneers' Historical Society)

a practice that had been followed at the 800-foot level in the Pittsburgh mine near Nevada City, California. In this method three holes were bored into a tight, strong barrel, one in the top and two on the sides. A funnel was inserted into the one at the top of the barrel and fitted tightly. Pipes were tapped into the other holes and some kind of valve or spigot arrangement attached to each. A smaller pipe, connected with a water supply, opened into the funnel on the barrel head. Upon turning on the water pressure, air was trapped and forced into the barrel through the two side pipes. The lower pipe acted as an outlet for the water and the upper one as an air discharge. By regulating the valves in the discharge pipes so that the water was let out as rapidly as it entered and by setting the end of the intake water pipe at the proper height above the throat of the funnel, a strong blast of air could be maintained.

Such devices, while a mechanization of sorts, were rapidly replaced in the late 1800's and early 1900's by electric fans, used in conjunction with mechanized air current control devices. In 1912 at the 2,000-foot level of the Union Mine at Virginia City, Nevada, a Sturtevant multivane fan was in operation, worked by a 20 horsepower motor, while in the same year at the Copper Queen Mine at Bisbee, Arizona, regulators appeared in the main haulage drifts which were automatically operated by a system of latches set in the walls so that the ore trains did not have to stop to open and close ventilation control doors.

At the New Almaden quicksilver mine in 1890, all of the different levels were connected by shafts and winzes to ensure free circulation of air through all the workings. Nevertheless, in the long cross-cuts and drifts remote from the main natural ventilation currents, the air became exhaustingly hot, and some form of artifical ventilation became necessary. This was achieved by the placement of doors, which forced the air current to take a certain direction, or by wooden boxes or sheet-iron pipes, placed so that the air was compelled to pass through these conduits towards the face of the drift. When these failed, blowers or fans were used, driven either by hand power or by compressed air. The latter was by far the simplest way of ventilating drifts when fans were not available. The exhausted air from compressed air drills also kept the mine atmosphere fresh during the actual process of drilling. After blasting, the stopcock conveying compressed air to the drill could be turned on, the compressed air rushing onto the face of the drift, thus reducing the temperature and blowing out the noxious gases and dust formed by the blasting. Despite the introduction of fans, the compressed air pipe remained one of the primary sources of fresh air in underground mines after 1872.

Probably the greatest change in mining methods after 1872, however, was not the introduction of new machinery and equipment, but rather the introduction of large-scale methods, such as block-caving in underground mining and both strip and open pit mining for surface deposits. It was the new equipment, however, that made such large volume systems feasible, with drilling, loading, and hauling equipment of large capacities vital to the efficiency of any mass mining method.

2. Changes in Copper Mining

Although the small-scale mining methods in use prior to the 1880's had been well suited to the mining of precious metals and high-grade copper, it was the newer techniques that significantly aided in the development of the West's base metal and industrial mineral resources. In 1861, copper had been first produced in the West from the Sierra Nevada foothills copper-zinc belt in California. Civil War demand for the red metal stimulated production.[66] In 1865, the smelting of oxidized copper ores began at Silver Bell, Arizona,[67] and the mining of oxidized copper ores began at Morenci, Arizona, in 1879.[68] Mines at Butte, Montana, started producing copper regularly in 1882, after the coming of the railroad gave access to a district formerly considered remote.[69] The copper district of Jerome, Arizona, started production in 1888,[70] and the high-grade oxidized copper ores at Bisbee, Arizona, began to be mined at about the same time, as did those at Globe, Arizona.[71]

Before the technology of cheap, large-scale mining methods came West, together with improved methods of concentration, the mining of copper had been confined to high-grade deposits such as those at Butte, Montana, and Jerome, Globe, and Bisbee in Arizona, which contained about six percent copper. Six percent copper ore contains 120 pounds of copper per ton of rock. With the copper price in the early days averaging 15 cents per pound, such ore would have a gross contained value of $18 per ton. Precious metals, usually present, would normally raise this to $20. None of the early copper operations were persistently successful as economic ventures until local smelters were built, thus greatly easing the transportation problem and reducing freight costs. In contrast, one to two percent copper ore, a common grade for the early porphyry coppers, with a 15 cent per pound copper price would have a gross contained value of from three to six dollars. Obviously, extremely cheap methods of mining and milling were necessary to turn such mineral deposits into successful mines.

The development of the porphyry coppers, relatively low-grade deposits containing immense tonnages of rock possessing less than three percent copper, started with Bingham, Utah, in 1907. The development of technology to effectively mine and process those low-grade deposits was the most important factor in bringing in many new centers of copper production in the West. Ely, Nevada, followed Bingham in 1908, while Ray and Miami, Arizona, and Santa Rita, New Mexico, were brought in in 1911. Inspiration, Arizona, started in 1915, Ajo, Arizona, in 1917, Bagdad, Arizona, in 1937, and Morenci, Arizona (as a porphyry), in 1939.

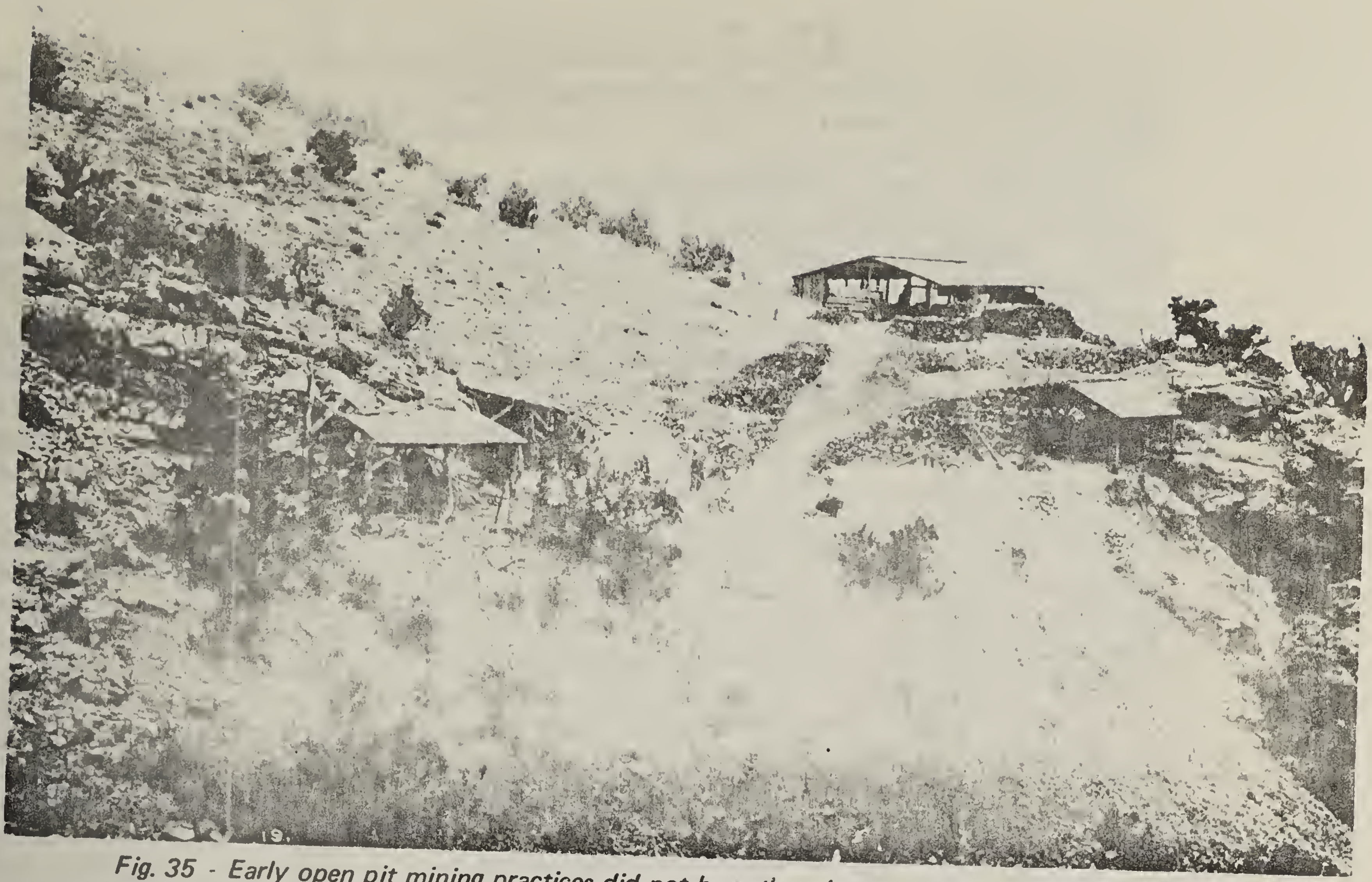


Fig. 35 - Early open pit mining practices did not have the advantage of large-scale materials handling equipment nor did they involve extensive development of broad mining systems. Large open pit mining did not really start in the West until the initiation of the Bingham Canyon mine of the Utah Copper Company in 1907. (Photo courtesy of Arizona Pioneers' Historical Society)

Cheap surface mining and mechanization were the keys to success for the porphyries. Large daily tonnages of ore were mined by power shovels (after being drilled by churn drills and broken by blasting) and hauled to the mill in gondola railroad cars (later mainly by large-capacity trucks). This was truly a revolution in western mining. Other base metal production in the West was also enhanced by the development of more efficient mining methods as well as by the increasing demands of a growing technological society.

Prior to World War I, there had been next to no demand for molybdenum, but the war stimulated demand for an alloy to make harder, stronger steel. In 1915, major production came from Wulfenite (lead molybdate) deposits in Arizona, although some molybdenite (molybdenum sulfide) ore was mined at Climax, Colorado.[72] Demand fell off during the post-war depression, but revived in 1923. At that time, deposits at Questa, New Mexico, supplied most of the nation's molybdenum, followed by Climax, which soon out-produced Questa. The production of molybdenum as a by-product in porphyry copper mining, now an extremely important source of molybdenum, started mainly only after 1947. The increase in the importance of the Climax operations came largely as the result of the introduction of large-scale caving methods underground.

3. Changes in Iron Mining

Iron mining in the West likewise gained from the advance of technological progress. Sporadic iron mining commenced in Utah in 1852 and may have been going on in 1860. Relatively important western iron mining was non-existent, however, in a region which had no markets of its own and no transportation to eastern markets. In 1902, however, the mining of iron ore began in the Hartville district, 80 miles north of Cheyenne, Wyoming, and in the early 1920's the United States Steel Corporation built a steel works at Provo, 30 miles south of Salt Lake City, Utah. The iron ore used at Provo came from the Iron Springs district in far Southwestern Utah.[73]

The nation's main iron ore fields were located in the late 1800's in Alabama, Colorado, Connecticut, Massachusetts, Georgia, Kentucky, Maryland, Michigan, Minnesota, Missouri, Montana, New Jersey, New Mexico, Utah, New York, North Carolina, Ohio, Oregon, Pennsylvania, Tennessee, Texas, Virginia, and Wisconsin, but by far the most important (in terms of total output) were the mines of the Upper Peninsula of Michigan. Pennsylvania, however, led the way in limonite, although the oldest and most important iron mine anywhere in the country (operating since 1740 and still working) was then at Cornwall, Pennsylvania, and was remarkable for its rich magnetite ores. Nevertheless, Michigan produced the most hematite, and New York the most magnetite. The richest ores were to be found in Minnesota and the poorest in Georgia and North Carolina.

Mining methods varied from place to place according to the nature of the deposits. In the Lake Superior district, where the deposits were hematite and of high-grade Bessemer quality, the ore was found in flat deposits. In the Mesabi district of Minnesota, it was almost 100 miles in length and 90 feet thick, and so easily worked that at many mines not a single hole had to be drilled for blasting. At Iron Mountain, Missouri, however, the ore had to be mined by more conventional methods, but in Massachusetts, open pit mining was also used.

The iron ore deposits of the West have been mined by open pit methods. This includes not only those operated in the early 1900's but also those developed during World War II. The important production of iron ore started in Nevada in 1943, when ore from the Buena Vista Hills, southeast of Lovelock, was used mainly in heavy concrete aggregate for ship ballast during World War II. Significant production of iron ores in California started in 1942, when the Kaiser Steel Company opened the Vulcan Iron Mine in San Bernardino County to supply their steel plant at Fontana.

4. Changes in Precious Metal Mining

While copper and other base metals were most often involved in the changes in minerals production that took place in the United States between the 1870's and the 1940's, the production of precious metals remained an important facet of western mining. Between 1860 and 1934, United States gold production fluctuated between less than two million ounces and four million ounces per year. With the increase in the price of gold from $20.67 per ounce to $35.00 per ounce, production expanded so that in 1940 it reached an all-time high of nearly five million ounces. In October 1942, however, the mining of gold was prohibited except as a by-product in the mining of metals critical to the war effort. Although the ban was lifted after World War II, costs rose rapidly after the suspension of wartime wage and price controls, while the price of gold was frozen. The Homestake Mine in South Dakota was one of the few mines producing only gold to reopen, and in 1947 was almost the only one of such mines in existence in the United States.[74]

With the advent of mining in large, low-grade disseminated copper deposits, an important new source of gold was tapped.[75] While the gold content per ton of porphyry copper ore was very low, the immense scale of mining resulted in a considerable contribution to domestic gold production. Important as the contribution of the porphyry coppers was, even in 1947 it was still being exceeded by that of "straight" gold mines and placers. By the end of World War II, base metal ores (mostly porphyry copper ores) accounted for less than 30 percent of total domestic gold production, while precious metal lode mines (including silver mines) provided nearly 40 percent of the nation's gold output. The Homestake Mine accounted for a major share of the lode mine production. Bucket line dredges, still working California placer deposits, accounted for the remainder (nearly a third) of the gold mined in the United States.

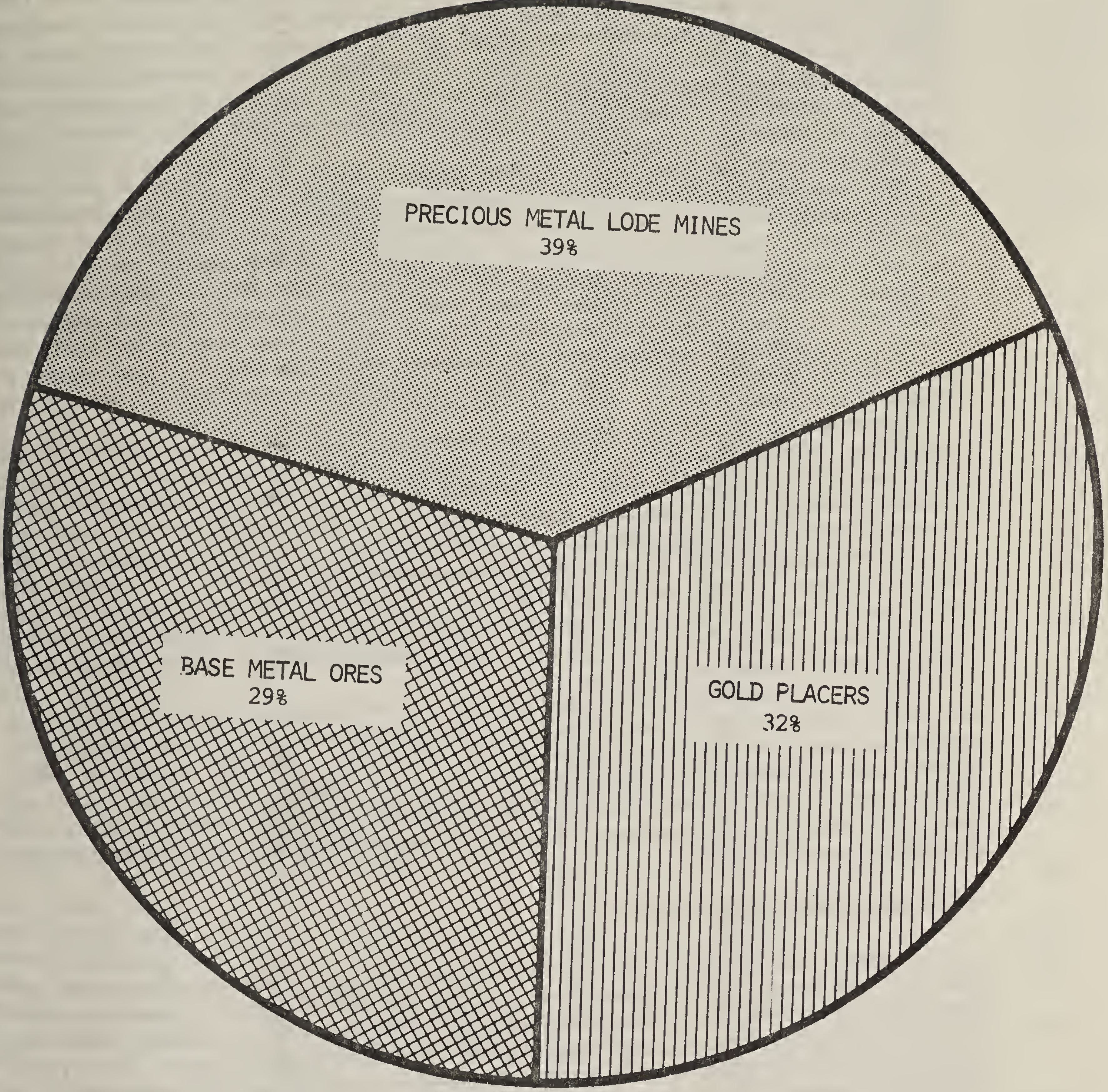


Fig. 36 - The source of gold mined in the United States in 1947. Despite the rising importance of by-product gold from porphyry copper ores and the closing of gold mines during World War II, lode and placer gold deposits still provided more than 70 percent of domestic output in the late 1940's. Source of data: U.S. Bureau of Mines Minerals Yearbook, 1947.

Many silver and silver-gold districts were brought into production in the Western United States between 1860 and 1947, but most of these were virtually exhausted by the mid-1940's. The mining of ores yielding silver only, as well as those of both silver and gold, has always been strongly affected by the price of silver, which dropped radically about 1893 when the government demonetized silver. The effect on the number of silver and silver-gold districts brought into production was severe. By 1947, however, nearly three-fourths of domestic silver production came as a product of base-metal mining, while only one-quarter came from silver and silver-gold ores.[76] The result was that the price of silver came to have practically no effect on silver production, which become relatively inflexible except as it depended on demand for base metals.

The silver-lead-zinc deposits of the Coeur d'Alene district, Idaho, placed in production in 1886, were still heavily productive, however, in 1947. In fact, in the early 1930's, the so-called Silver Belt in that district had been discovered. There, silver was more closely associated with copper than with lead, and the value of the silver exceeded that of the base metals.[77] Development of the Silver Belt has continued to date, and it is now the leading producer of silver in the United States. The important silver by-product lead-zinc districts of Park City and Tintic, Utah, had declined by 1947, but each has been revived since. The United States and Lark lead-zinc mines at Bingham, Utah, were also important sources of silver. By 1947, lead-zinc and more complex base-metal ores accounted for over half of domestic silver production.[78]

Copper mining in the West nearly everywhere produced silver as a by-product. Before exploitation of the porphyry coppers began in 1907, copper mining had been confined to high-grade veins (Butte, Montana; Old Dominion, Arizona), massive deposits in schist (Jerome, Arizona), or replacement deposits in limestone (Bisbee and Morenci, Arizona). These high-grade copper deposits yielded considerable silver. From 1884 to 1898, ore from the Anaconda copper veins at Butte averaged 4.5 ounces silver per ton.[79] In contrast, the porphyry coppers contain only from .02 to .11 ounces of silver per ton, but a mine producing 10 million tons of ore per year would furnish from 200,000 to more than a million ounces of silver. By 1947 copper ores furnished nearly a quarter of the silver produced in the United States.[80]

Silver was also important in the continued growth of lead production in the West after the 1860's. Attracted by the rich silver in western lead deposits, several were brought into production early in the period. Eureka and White Pine, Nevada, started in 1869, Cottonwood, Utah, in 1870, Park City, Utah, in 1872, Leadville, Colorado, in 1875, and Tintic, Utah, in 1879. Mining in all of these districts started on silver-lead carbonate ores near the surface, but all encountered increasing concentrations of zinc at depth, as they penetrated the sulfide zone.

5. Changes in Mining Other Metals

Zinc production, however, had to await western population and industry growth. In 1902 the New Jersey Zinc Company started mining zinc ores at Hanover, New Mexico.[81] Production of zinc from the Magdalena district, 100 miles north of Hanover, began in 1903.[82] Production of zinc in Utah began in 1904 in the San Francisco district, and in 1905 the Park City district started producing zinc, followed by Bingham in 1909 and by Tintic in 1912.[83] The mine at Goodsprings, Nevada, became a zinc producer in 1906.[84]

The production of other metals (except mercury) did not begin in significant proportions in the West until nearly the middle of the 20th Century. California, however, has been the chief source of United States mercury production ever since the New Almaden mine started producing in 1850. Followed by the New Idria mine in 1858, most of the important past and present quicksilver mines had been put in production by 1875.[85] A few mines with modest reserves of mercury minerals came into production during the present century in Oregon and Idaho, as well as in Nevada. The Cordero Mine in Northwestern Nevada started production as recently as 1940.[86]

Table 26

OPERATING DATA FOR GOLD-DREDGING OPERATIONS IN THE UNITED STATES IN THE 1930's

	Gravel				
Dredge and Year	Nature	Average depth, feet	Average Monthly Yardage Handled	Average Operating Time per Day (hours)	Total Operating Cost per Cubic Yard
La Grange, Calif., 1932	Loose, no clay, 5 percent boulders.	30	217,000	20	$0.038
Lancha Plana, Calif.	Medium tight, 20 percent clay and loam.	40	63,500	18	.147
Natomas, Calif., 1932					
No. 2	------------	30	152,000	20	.053
No. 4	------------	28	271,000	20	.038
No. 5	------------	50	147,000	18	.073
No. 7	------------	36	177,000	20	.053
No. 8	------------	58	237,000	20	.052
No. 10	------------	51	259,000	20	.045
Total and average	------------	—	1,243,000	20	.050
Placer Development Co., Calif., 1932	Loose, few boulders, little clay.	25	100,000	20	.0797
Shasta Butte, Calif., 1932	Fair digging, some clay and hard gravel.	—	130,000	18	.062
Trinity, Calif., 1932	------------	25	100,000	20	.060[a]
Yuba, Calif., 1932					
No. 14	------------	54	900,000	---	.041[a]
No. 15	------------	58	900,000	---	.041[a]
No. 19	------------	74	900,000	---	.041[a]
Continental, Colo., 1932	Some boulders and clay.	—	122,000	20	.067
American, Idaho, 1932	No boulders or clay.	15	50,000	20	.070
Idaho, Idaho, 1932	------------	20	75,000	22	.100
Empire, Oreg., 1932	------------	24	75,000	20	.062
Fisher & Baumhoff, Warren, Idaho, 1937	Few boulders.	20	120,000	21	.045[b]
Fisher & Baumhoff, Granite Creek, Idaho, 1937	80-85 percent sand and fine gravel.	23	42,500	---	.1415
Fisher & Baumhoff, Centerville, Idaho, 1937	80-85 percent sand and fine gravel.	23	133,000	---	.0758

[a] Excluding taxes, insurance, and administrative expense.

[b] Depreciation and depletion 2 to 2½ cents additional.

Source of data: S.D. Woodruff, *Methods of Working Coal and Metal Mines* New York: Pergamon Press, 1966, Vol. 3.

During the first half of the 20th Century the chief source for beryllium was the mineral beryl, containing about 11 percent beryllium oxide. United States production and consumption (largely from imports) of beryllium were negligible until 1941, when World War II stimulated demand through discovery of a number of wartime uses. The principal sources of beryl in the United States by 1947 were pegmatite dikes in South Dakota, Colorado, and New Mexico.[87] The mining of uranium minerals in the United States was also negligible before 1942, in which year the Atomic Energy Commission started a search for new deposits in connection with the Manhattan Project. No new deposits were found, however, and all production came from previously known deposits, chiefly in the Uravan district of Southwest Colorado.[88] By 1947, uranium mining was in the doldrums and known reserves were extremely low. In 1948, however, the Atomic Energy Commission initiated its ore purchasing program, after which thousands of deposits were discovered, and the small-scale mining of the earlier gold rushes was reincarnated in the great uranium boom of the 1940's and 1950's. Programs of subsidies, bonuses, technical assistance, and low cost capital loans also contributed to the boom.

6. Changes in Industrial Minerals Mining

The metal mining industries were not the only nonfuel mineral industries to undergo change during the period from 1872 to 1947, but the changes were not as marked in the production of industrial minerals. During the period from 1860 to 1947, the population of the United States grew from less than 80 million to approximately 130 million. A dramatic shift in population and industry was accomplished during this time. Early in the 1800's both population and industry were localized along the Eastern Seaboard, but a strong and definite movement toward the West had taken place by the end of the 19th Century. By 1947, a significant part of the nation's population lived on the Pacific Coast. There was a lag, however, between this population shift and industrial movement. Consequently, by 1947 the consumption of industrial raw materials in the Western States had not been as vigorous as in the East nor as it was to become in California during the next 20 years.

In 1880, there were 616 major limestone quarries in the United States, all located in states east of the Rocky Mountains. These produced nearly $6.9 million worth of limestone from a capital investment of about $10.6 million. Only small amounts of lime were produced in Colorado and California. At this time, the dominant domestic cement was natural rock cement (which differs in composition and properties from portland cement), most of which was produced in New York, Kentucky, Indiana, and Pennsylvania. In 1882, 3.25 million barrels of cement were produced in the United States, and of this only 85,000 barrels were portland cement. In 1882, a barrel of natural cement weighed 300 pounds and was worth $1.82. A barrel of portland cement weighed 400 pounds and was worth $2.25. Small amounts of cement were produced in Colorado, California, Oregon, and Washington, but California consumed comparatively large amounts of imported cement (100,000 barrels in 1881). The rebuilding of San Francisco after the great earthquake gave local cement manufacturers a strong market in 1906 and 1907, thereby establishing a vigorous local industry and production of cement in the Western States was begun on a significant scale.

Although deposits of limestone occur in every state, the 1930 production figures showed that dimension limestone was quarried in about half of them. Most dimension limestone at that time came from Indiana. Quarries for production of crushed and broken limestone were widely distributed and were increasing because of the intensive public work programs emphasizing construction and road building. Although this segment of the industry was established long ago, it grew from a small industry in 1880 to a large business in 1929, when 151 million tons of crushed limestone were produced. Of the leading 15 producing states in 1930, not one was west of the Rocky Mountains.

By 1941, the limestone industry of the United States produced 133 million tons of limestone for stone, 42.75 million tons of limestone for cement, and 12 million tons of limestone for lime. At this time the 11 Western States produced less than two percent of total United States production of limestone for stone (dimension and crushed and broken for all purposes except lime and cement), about 17 percent of the limestone for cement, and less than five percent of the limestone for lime. These figures illustrate the strong position of the cement industry of 1941 in the less populous 11 Western States compared to rather nominal production of limestone for other uses. The Western States produced about ten percent of the nation's cement between 1910 and the mid-1930's, but they nearly doubled this percentage of production by 1941.

The production of other industrial minerals used in the construction industry also increased in the West between 1872 and 1947. Gypsum, calcium sulfate plus water, had been used to make plaster from time immemorial. The first plaster mill in California was erected in 1875, using gypsum mined in Santa Barbara County. By 1947 many major deposits of gypsum had been developed and were in production, especially in California and Nevada. Bentonite, a member of the clay family, has the property of swelling when wet. For this reason, it is used for drilling muds and for other industrial and construction purposes. The enormous deposits of bentonite in Wyoming and South Dakota were well known by 1947, the first bentonite treatment plant having been built in 1921 near Medicine Bow, Wyoming.[89]

The production of some other industrial minerals in the West has not been quite so closely related to or dependent upon regional population growth. These are the minerals that serve national rather than regional or local markets. Early in the 1900's, in order to eliminate United States dependence on European sources of potash, the search for domestic deposits was begun. Although started in 1911, the search finally resulted in the start of production from the Carlsbad, New Mexico, deposits in 1931. Production of potash from the Searles Lake brines, however, had begun in 1916. Other chemical raw materials were also becoming important to the nation, and western sources were being utilized more and more. Natural soda ash (sodium carbonate) was discovered in Owens Lake, California, in 1885 and production was still underway in 1947. Soda ash had been produced from Searles Lake brines since 1927. Production did not begin from the enormous deposits of soda ash at Green River, Wyoming, until 1948.[90]

The borates, borax (sodium borate plus water) and other sodium and calcium borates, are limited to arid regions in the United States, notably Southeastern California and Nevada. In 1872 borax was first extracted from playa (dry lake) deposits in Nevada, and the production of borax from similar lakes in Death Valley, California, began in 1882. In 1890, exploitation of the calcium borate deposits of Calico, California, an old silver camp, began. Production of borates from the Searles Lake brine commenced in 1919, while development of the Kramer sodium borate deposits began in 1927.[91] While some of these deposits could be mined by standard surface methods, some required the development of new mining techniques.

The methods of solution mining, at least as far as they pertained to brine deposits, were in use by the early 1900's. Even what has been considered a relatively recent innovation, in-situ leaching, had been introduced well before 1947. One of the first applications of in-place leaching was in the early 1920's at the Ohio Copper Company mine at Bingham Canyon, Utah. There, leach solutions were distributed over the surface of a large hill overlying a portion of the caved zone of the underground mine. Slow percolation was used in the leaching because it was believed this method would promote the oxidizing conditions deemed favorable for continued and rapid dissolution of the copper sulfide minerals.

7. Changes in Beneficiation

The changing nature of the mineral commodities mined in the West after the 1860's had a pronounced effect on the minerals beneficiation process, perhaps more so than on mining itself. While the mining process remained essentially the same in principle, the beneficiation process expanded drastically and became far more complex than it had been previously. In fact, for many minerals, the process of beneficiation did not really come into existence until after 1870.

As in mining, the increased mechanization of existing processes formed an important part of the changes that occurred in minerals beneficiation. Most of this mechanization was first introduced in achieving size reduction and gravity concentration.

Size reduction is concerned with mechanically reducing the ore into the smallest feasible fragments. By 1860 there were several kinds of mechanical rock breakers on the market, but by 1900 a number of specialized machines had proved themselves. One of these was the *jaw crusher*. The principle of the jaw crusher was that of an eccentric on a shaft which at every revolution caused a moveable jaw to advance toward a stationary jaw. Lumps of ore that were dropped between the jaws were thus broken by succeeding bites, the fragments falling lower and being bitten again until they passed out through the bottom of the machine.

Gyratory crushers in existence in the 1890's were developed as an improvement on the jaw crusher. A machine of this type consisted of a fixed crushing surface in the form of the frustrum of an inverted cone. Around the axis of this cone gyrated a moveable crushing surface which had the shape of a conical frustrum in an erect position. The material to be broken was fed into the space between the two crushing surfaces, was crushed when the surfaces approached, and fell through when they receded.[92]

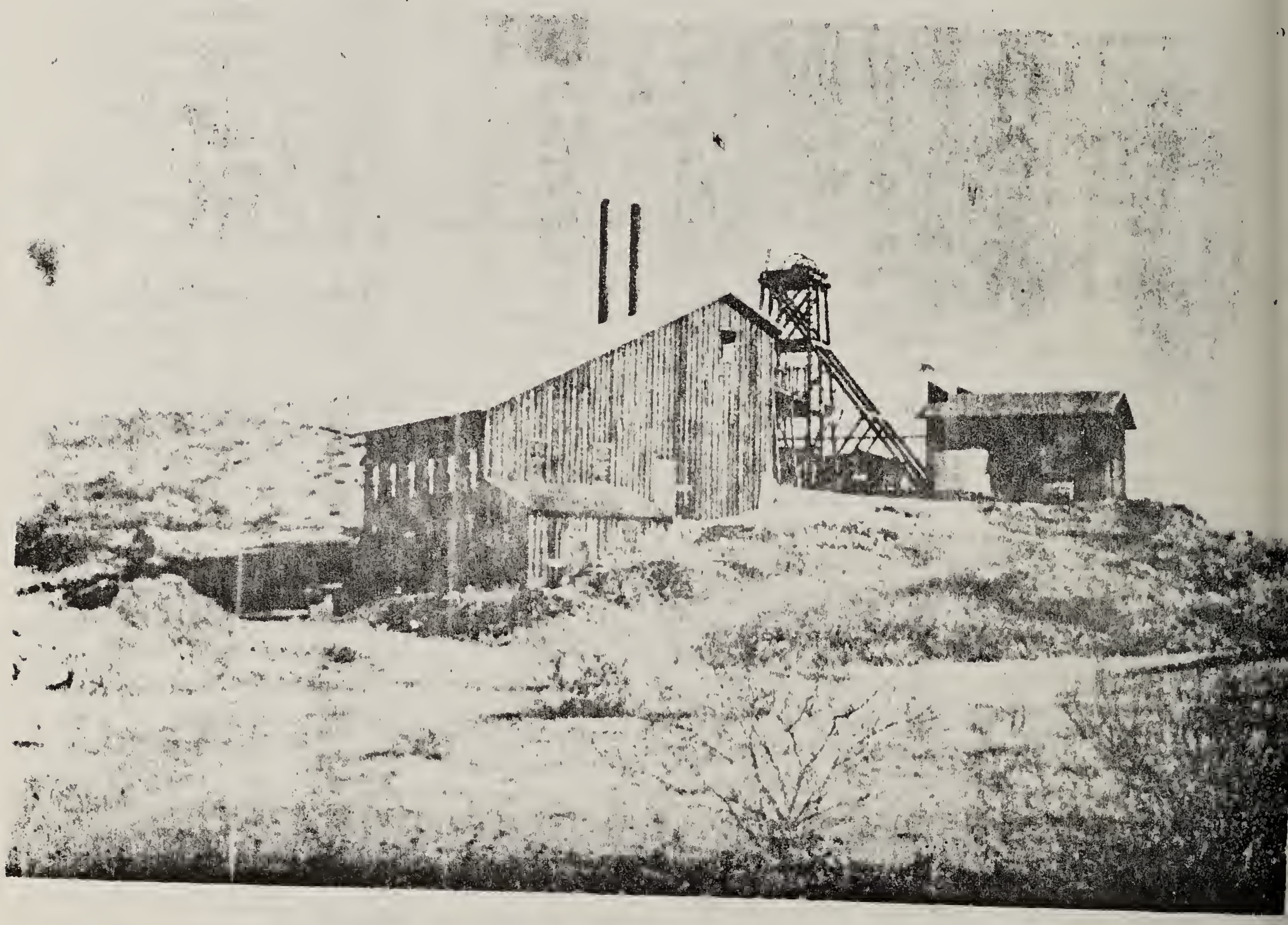


Fig. 37 - The Mohawk stamp mill near Mammoth, Arizona, in 1895. Although stamp mills were still widely used as both beneficiation and amalgamation machines in gold recovery after 1872, they were mostly replaced by various types of crushers and grinding mills in processing other minerals. The earlier types of milling equipment required comparatively little space and mills were frequently located at the mine shaft. (Photo courtesy of Arizona Pioneers' Historical Society)

A number of other crushing devices were also developed in the late 1800's. *Sledging rolls* were machines with one single-roll crusher or two massive rolls, armed with massive heavy projecting knobs or teeth and set horizontally. *Cone crushers* operated on the principle of a massive iron cone set on a pivot with its point facing downwards so that the rolling motion of the cone would crush the rock. There were many variations of this, including the disk crusher which was much in vogue from 1915 to 1920 but which has now become obsolete.

The *rolls crusher* was a rather simple machine for reducing the ore to about 20 mesh (a measure of particle size) after it had previously been through another type of ore breaker. The earliest types of rolls were known as Cornish rolls and worked on the principle of a weighted lever. The bearings for the rolls were rigidly fixed on the frame and so these were known as rigid rolls. Because of their tendency to stall and cause mechanical damage, however, they were soon superceded by spring rolls.[93]

Hammer mills had been in almost continuous use in Europe since the mid-1800's, but only occasionally in the United States as secondary crushers. They were really a series of flailing hammers, and were used almost entirely in the late 1800's in the United States as primary crushers for reducing quarry material such as phosphates, gypsum, asbestos rock, and cement rock.

The purpose of size reduction, of course, was to liberate the valuable minerals from the gangue. Not all ores required complex crushing equipment, however, even in the period from 1872 to 1947. Some ores were broken and upgraded simply by washing to disintegrate and float adhering clay or other fine grained materials from the coarser portion of the ore. The latter may or may not have been turned over to other processes for further concentration.[94] By 1900, there were various types of washers used, including trough washers, log washers, wash trommels, washing pans, and hydraulic giants. These same machines were also sometimes used to enrich partly concentrated products.[95]

The liberation of ore minerals from gangue minerals, however, was most often accomplished by a sequence of crushing and grinding. In the early 1900's, preliminary breaking was done by blasting in the mine, calcining for friability (with or without quenching), using hand tools such as sledge, spalling, or cobbing hammers, using machines such as steam and drop hammers, rock breakers, or special forms of rolls, steam stamps, pneumatic stamps, spring stamps, or gravity stamps, and grinders such as ball and rod mills.[96]

Grinding was the next stage in size reduction. It was designed to produce a fine powder for the processes of concentrating, and was developed in two stages, wet grinding and dry grinding. Wet grinding was achieved through the evolution of tumbling mills and tube mills. A tumbling mill consisted chiefly of a cylinder mounted on a horizontal axis and in which spun steel or iron balls which ground the particles of ore inside with an abrasive action, the action being helped by the introduction of water. They appeared in the American West in the 1880's in this form, although in Cornwall, at about the same time, granite chunks were being used instead of the iron balls. Later, the wet grinding method was improved by the introduction of steel rods as tumblers. Tube mills were used for even finer grinding, the tumbling charge being usually balls or pebbles or a mixture of both. Sometimes scrap iron replaced the pebbles. These wet grinding machines became standard in America after they had been uniformly adopted in South Africa as an essential part of the cyanide process for gold recovery.

Dry grinding was a different matter insofar as it was applicable to soft materials as clay, chalk, talc, salt, ochre, lime, and gypsum. But the actual milling process was almost the same as for the harder materials with the addition of attrition and buhr mills, injector-type mills, and pan or chaser mills, and, of course, with the absence of water.

During the late 1800's, in order to facilitate the wet grinding of old ores, there were numerous attempts at the mechanization of the Chilean mill and the *arrastra*, and these resulted in the evolution of the Huntington mill. The latter consisted of a series of circular pestles hung by yokes so as to revolve within a casing, the centrifugal action bringing them into close contact with a circular steel ring die. In this way the ore was pulverized by being thrown into the path of these pestles.

Depending upon the concentration process used in the late 1800's and early 1900's, crushed and ground or washed ore may or may not have been sized by *screening* or *classification*. Screens or sieves served to separate the finer particles from the coarser particles, the purpose of screen sizing was to divide the crushed ore into a series of products which could readily be concentrated in the machines that followed. Several types of sizing screens were used in the early 1900's, namely, grizzlies or bar screens, perforated plates, wire cloth screens, shaking screens, shaking riddles, revolving screens, and trommels.[97]

Classifiers were developed for grading the ore below the physical limit of fine screening. The principle of classification depended upon the ability of ore particles to settle in water. Of two particles of equal size having different specific gravities, the heavier will fall faster, and of two particles having the same specific gravities, the larger will settle faster in water. This latter principle was used in size classification, while the former was used in several forms of gravity concentration.

All mineral classifiers in use by the early 1900's had a current of water flowing through them which carried forward the suspended grains. Some classifiers also used a rising current of clear water which was added from below the falling particles, and these were called hydraulic classifiers. The hydraulic classifiers were mainly trough or shallow pocket, deep pocket, or tubular hydraulic classifiers. The other classifiers used included surface current box classifiers, whole current box classifiers, distributing boxes, unwatering boxes, settling tanks, and clarifying reservoirs.[98] The latter three units were (and are) also called *thickeners*.

8. Changes in Concentration

Once ores had been crushed and ground to the proper particle size, they were concentrated. It was in the *concentration* phase of beneficiation that probably the most notable changes took place between 1872 and 1947. Both the changes and their effects have had a profound impact on the present utilization of mineral resources.

The purpose of concentrating ores was to separate the useful from the useless and to sort out the valuable minerals from each other. The principle on which early concentration was based was the simple one of gravity, i.e., that when pieces of different minerals of the same size are subjected to a flow of water sufficient to move them along, the lighter material is washed away quickest. Except for some magnetic separators and hand picking operations, all of the common concentrating devices used in the late 1800's and early 1900's acted upon a mineral-water pulp. This pulp was prepared by the various methods previously mentioned. Washing and/or crushing and grinding liberated the mineral particles, while classification put the pulp in condition best suited for a particular concentration process.

Gravity concentration is an ancient art that had been practiced in Europe for many centuries before it was brought to the United States, where it probably started in New Jersey about 1750 with the concentration of copper ore.[99] The prime example of a simple gravity separation device is, as has been noted, the prospector's gold pan. Before the advent of the *froth flotation process* (which first appeared in the United States in 1911),[100] gravity concentration methods were the most important of all concentrating processes. Early gravity concentration practice was aimed at recovering the desired ore minerals at the coarsest possible size with the least production of slimes, and this is still the case. Slimes are the extremely fine-grained product that often carries valuable minerals which cannot readily be recovered by gravity concentration processes. The least amount of slime was produced by avoiding overcrushing and overgrinding.

The predominate gravity concentration equipment used by the early 1900's were jigs, vanners, bumping and jerking tables, film sizing tables, riffles, sieves and pans, including prospecting pans.[101] One of the first methods to be developed in the 1800's was known as *jigging* or *hutching* and involved minerals of comparatively large grain size after they had been delivered by the ore crusher. In jigging, the charge of ore was placed in a frame which had at the bottom a wire gauze or perforated metal plate, wherein it was subjected to a series of small jerks that followed each other quickly. In this way the lighter particles were gradually forced to the top, while the heavier ones collected at the bottom. The jigging was normally of two kinds. One entailed jerking the container with an upward and downward motion in a tank of water. The other operated by forcing water upwards from the bottom of the container by means of a piston. By the 1890's, these two main types of jigs had been developed, and they remain today the standard types, fixed-sieve jigs and moveable-sieve jigs.

In the gravity concentration plants in operation before World War II, after the jigging and classification, the next step was to subject the rough concentrate to further concentration. The most widely used piece of apparatus in this next step was the *shaking table*, sometimes called a *vanner*, of which there were many varieties, each adapted to the ore they were to concentrate. One of the earliest types (used a good deal in the silver district of Gilpin County, Colorado) had a table in which the shaking was in the direction of the slope, causing the heavy material to climb against the flow of the pulp, but this type has now become obsolete.

Of all the vibrating tables developed, perhaps the most celebrated and widely used was the *Wilfley*, an ideal contrivance for dealing with lead, zinc, copper, gold, and silver ores. It was a side-slope shaking table with riffles spread in a diagonal line over a little more than half of its surface. A modification of the Wilfley Table was called the Butchart or National Table. Its riffles were bent diagonally and produced a wave effect along the table, thus helping to bring the gangue to the surface and allowing it to be washed away. Another modified version was the Card Table, in which the riffles were triangular and cut into the deck, again helping the precipitation of heavier particles. This type was well known in the Bunker Hill and Sullivan lead-silver mills of Idaho and in a few mills in Southwestern and Central Colorado where it was used for the treatment of complex sulfide ores.

Fig. 38 - The concentrator at Clifton, Arizona, in the 1890's. After 1872 and before the introduction of froth flotation in the early 1900's, virtually all concentration of metallic ores was by gravity methods. These usually involved batteries of machines such as jigs and tables and required an abundant supply of water. (Photo courtesy of Arizona Pioneers' Historical Society)

Every refinement of the Wilfley Table seemed to depend on the design of the riffles, which in turn depended on the work to be done. For instance, the Garfield Table had the riffles extending the full length from the head motion to the concentrate and was ideal for rough work. The Plat-O-Table was designed for the same purpose, but it had a greater effectiveness since there were several decks, one above the other. It was to be found at the Idaho-Maryland mill, at Grass Valley, at the Ray Consolidated mill, the Anaconda mill, and at that of the Connecticut Zinc Corporation at Orongo, Missouri.

The *vanner* was another version of the shaking table. There were hosts of varieties, but all had one common denominator, a smooth and slightly inclined or horizontal surface over which the ore was spread by a relatively small but continuous quantity of water and forced to undergo a continued disturbance by "end shake," "side shake," or some other violent movement.

One other gravity concentration process, *buddling*, was in wide use by 1900. The buddle was a water separator based on the principle that the different inertias of particles of different sizes and specific gravities, when subjected to the impulse of moving water, cause the different particles to travel on different paths. There were many different versions of the buddle, but they normally consisted of a circular pot about 22 feet in diameter and two feet deep at the circumference (which was the center-head) with a raised center of about ten feet in diameter and a floor falling away towards the outer circle at a slope of about one inch for a length of six feet. The material to be concentrated was brought to the center of the buddle by launders, into which flowed a constant stream of water that was evenly and finely distributed over the raised center from a revolving pan that carried a number of spouts. Thus, a thin film of water was made to flow slowly and in a controlled manner outwards and over the whole sloping floor to the circumference of the buddle. In its passage down the slope, the material, held in suspension by the water, was gradually deposited according to its specific gravity. As a result, the ore (being the heaviest) was the first to be thrown down and therefore was concentrated towards the center of the buddle. From there, the ore would be put through a series of buddles until it could be concentrated no more. The buddle, although originating in Germany, was in use in Cornwall as early as the 18th Century in the concentrating of tin ores, but came to the United States only in the latter part of the 19th Century.

Most mineral concentration processes in use prior to 1872, as well as most of those developed after that date, used water to a great extent. An adequate supply of water for beneficiation purposes thus became a critical factor early in mineral production and subsequently increased in importance. All concentration methods, however, have not used water.

One of the early methods of ore beneficiation to involve only dry ore was *hand picking*. For some ores it is still a highly effective method in some parts of the world, but in the United States it began to be replaced by more mechanized methods in the first half of the 20th Century. Hand picking was, as its name implies, the operation of separating by hand high-grade ore from barren or low-grade rock. In order for this concentration process to be feasible there must be a visible or otherwise easily detectable and marked difference between high-grade pieces of ore and low-grade or barren pieces of rock. In the early 1900's, hand picking usually followed the coarse crushing stage. Sometimes *cobbing* accompanied hand picking, in which ore was further freed from waste by striking it off with a hammer.

Another concentration process that usually involved water was based on the magnetic properties of certain ore minerals. By the early 1900's, magnetic separation had been confined almost entirely to the separation of iron ores from gangue or from other heavy minerals. Magnetite is an iron mineral that is naturally attracted to a magnet, and magnetite could therefore be separated directly, but limonite, pyrite, hematite, and siderite were almost always given a preliminary roasting before magnetic separation to convert them into a magnetic oxide.

The beneficiation of iron ores in the early 1900's was based on both magnetic and gravity concentration methods. In both methods, the sizing of the material was regarded as of prime importance. The amount of crushing and the degree of fineness required depended on the size of the mineral crystals in the crude ore, the particular foreign matter to be eliminated, the purpose for which the concentrate was to be used, and the condition of the ore and the methods employed for the final separation.

In many cases, magnetic separation was really a refinement of the process that involved washing, screening, and jigging. The magnetic separator (of which there were several makes) was often incorporated in the jig. The ore, having been crushed to the required size through multiple-jaw crushers, sometimes wet and sometimes dry, was fed onto a distributing belt armed with powerful magnets which picked up the magnetic particles of ore, leaving the non-magnetic gangue to be carried away.

The same method could be used for treating waste dumps. For instance, at the Tilly Foster Mine in New York, the waste was crushed by jaw crushers at the dump, carried to the mill where it passed under ball stamps, and then was elevated to the electrical separating belts. Magnetic concentration was said to have reached a high level of efficiency at the Croton mines in New York, where some preliminary roasting also had to take place (because of the presence of sulfur) before the ore reached the electrical belts.

Throughout the first half of the 20th Century, magnetic concentrating plants grew to be more mechanically efficient than ever before, cheap to operate, and capable of handling large tonnages. But otherwise the technology did not change to any appreciable degree. By 1947, such a plant still possessed crushers of the usual jaw type and the drying plant to cope with ores like those from Cuyuna in Northern Minnesota which might contain as much as 30 percent water. Sintering plants often became necessary as adjuncts to the drying plants to drive off the water and agglomerate the fines into porous lumps, a procedure which also improved the behavior of the concentrate in the blast furnace.

In wet concentrating, a washing plant became inevitable and the ores were tumbled in water to remove the clay-bound sand. Almost 80 percent of Minnesota ore came to go through this process by 1947. The older practice there had been to log-wash down to two inches size and then to rewash in turbo-washers, finally concentrating the granular settlings on shaking tables. But, as at the Canisteo plant of the Oliver Iron Mining Company at Coleraine, Minnesota, the log-washers were replaced by screens and classifiers.

In Michigan, on the other hand, the typical Lake Superior concentrating plant became a combination of coarse concentrators (normally jigs) for rejecting the coarse gangue and washing apparatus for removing the free sand and the fine gangue produced by crushing.

Magnetic plants were still used to treat the Eastern magnetic ores that had been mined since before 1800. The dry-magnetic mills were at first typical of the methods that had been in operation for many years, but because of the demands for higher grade concentrates, these were eventually displaced by wet-magnetic concentrators. The principle followed in all concentrations of magnetic ore was to scalp out the middling at coarse sizes with relatively high magnetic intensities, reject the tailing, and then recrush the middling. This process was first achieved with success about 1924 at the mill of the Mesabi Iron Company, although in this particular instance it was found that the concentrate so produced could not compete with concentrates of hematite ore.

Magnetic separation later was carried out by many concerns throughout the East. The Warren Foundry and Pipe Corporation at Wharton, New Jersey (which in 1967 possessed the only dry-magnetic mill still operating in the United States), the Republic Steel Company in New York, the Mesabi Iron Company at Babbit, Minnesota, and the Alan Wood Steel Company in their Scrub Oaks mill near Dover, New Jersey, all introduced and continued to use this method up to mid-century.

Alabama ores, being of a special kind, had to undergo special treatment. The structure of the red ores of the Birmingham district, sheets of very fine hematite mixed with lime carbonate, grains of quartz, and consolidated clays, prevented the mining of low-grade ores because of an inability to wash them. The main emphasis thus was placed on the concentrating of the brown ores through the usual processes of screening, washing, and jigging. The problem of the red ores was partially solved, however, by the invention of the

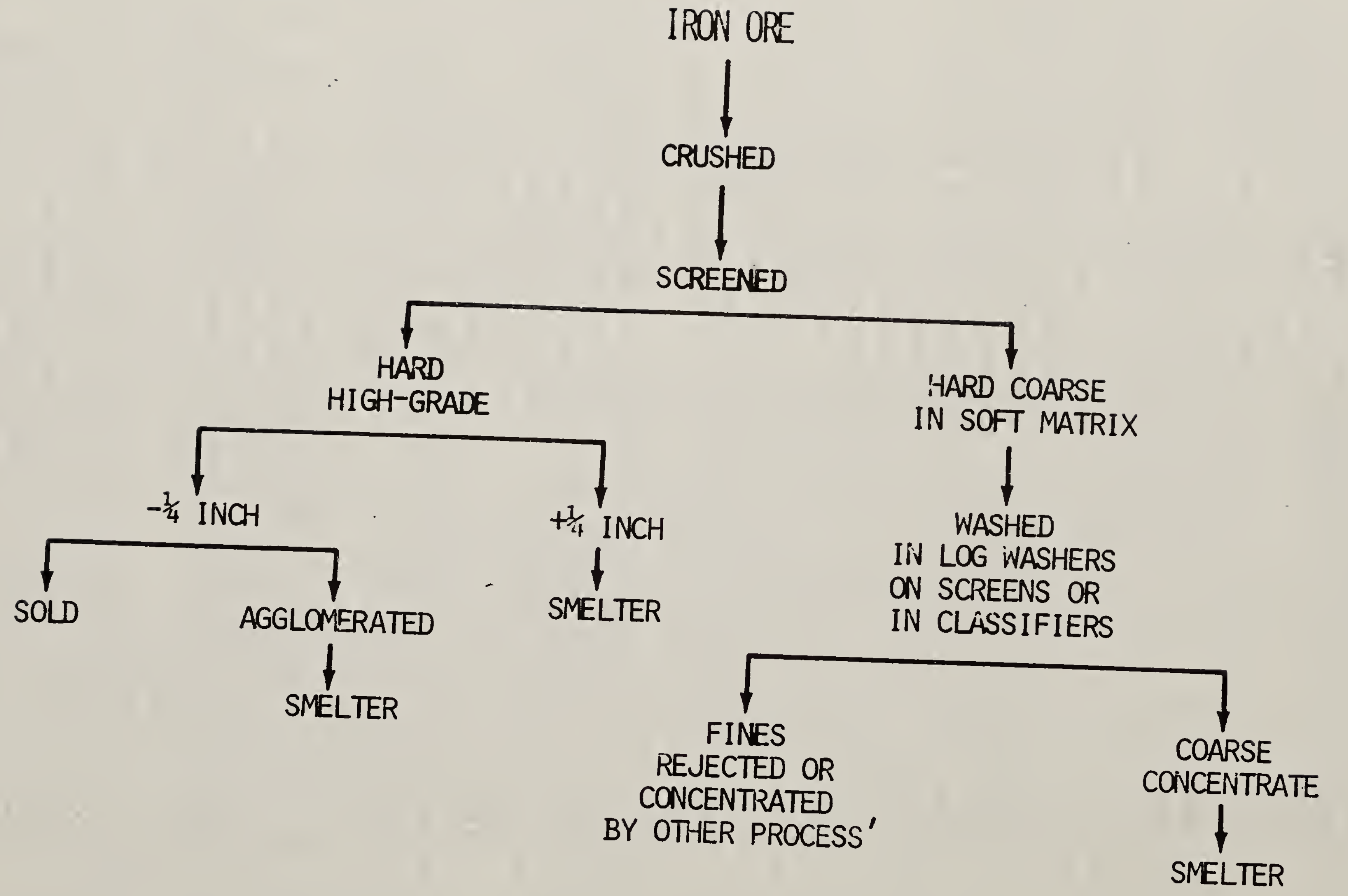

IRON ORE
CRUSHED
SCREENED
HARD HIGH-GRADE
HARD COARSE IN SOFT MATRIX
-¼ INCH
+¼ INCH
SOLD
AGGLOMERATED
SMELTER
SMELTER
WASHED IN LOG WASHERS ON SCREENS OR IN CLASSIFIERS
FINES REJECTED OR CONCENTRATED BY OTHER PROCESS'
COARSE CONCENTRATE
SMELTER

Fig. 39 - The beneficiation process for early iron ores was relatively simple and generally involved only sizing and washing. The development of some lower-grade ores in the early 1900's added gravity and magnetic concentration steps to the process.

Spaulding concentrator, built in 1943, the principle of which was to scuff off the very fine iron mineral from the silica by light treatment in rod mills, followed by concentration on tables.

Despite the importance of magnetic and gravity methods to the production of minerals in the Eastern United States, in the West the most important innovation in minerals beneficiation after 1872 was undoubtedly the introduction of *froth flotation*. Prior to 1915, most metallic mineral concentration was normally by gravity methods in which the finely-ground ore was carried by water in suspension to tables which vibrated, giving an effect similar to that of the gold miner's pan. The light gangue minerals were carried along and off the end of the table while the heavy sulfides went off the sides. By 1915, however, concentration by froth flotation had been well developed. In this method the finely-ground ore was carried by water in suspension to flotation cells. Various chemicals and emulsifiers were added, producing a bubbly froth. Quartz and other valueless constituents of the ore fell to the bottom of the cells, while the sulfide (which adhered to the bubbles) was carried up and over the top of the cell by the froth and deposited in launders which carried it away to be filtered and dried. Development of the froth flotation method had an enormous effect on the exploitation of large, low-grade sulfide deposits. Today the usual procedure in metallic sulfide beneficiation is crushing and grinding, and then flotation before sending to the smelter.

The development of *differential flotation*, whereby sulfides of the various metals occurring in complex ores could be separated from one another, greatly facilitated the production of zinc from such ores. The Bunker Hill Company in the Coeur d'Alene district of Idaho presently mines such ores and was among the first to separate zinc sulfides using differential flotation. In 1928 Bunker Hill started an electrolytic zinc reduction plant to replace the slow and expensive smelting method that had previously been used to produce slab zinc from sulfide.[102]

The development of froth flotation also had an influence on the utilization of sulfide deposits that had previously been concentrated by gravity methods or sent directly to smelters without concentration. At some properties, the introduction of froth flotation permitted the expansion of ore reserves to lower-grade areas and the introduction of new mining methods.

In 1923 a concentrator was built at Bisbee, Arizona, to treat disseminated copper ore in the northwestern portion of the Sacramento Hill porphyry intrusive. This was in effect the predecessor of the much larger Lavender pit which came into production after 1947. The Sacramento pit, a relatively small surface operation, reached its maximum feasible depth in 1929. Some block-caving was tried below it, but the entire operation was relatively short-lived.[103] Even froth flotation could not overcome the effects of the Great Depression on the demand for copper.

9. Changes in the Advanced Processing of Copper

The changes that occurred between 1872 and 1947 in the advanced processing of copper ores were just as typical of other metallic minerals as were the changes in copper beneficiation. While the innovations made in the advanced processing of copper since World War I have been largely modifications of the same basic process, the changes that occurred in the late 1800's were far more fundamental. In these years, many metallurgical processes already well-known in Europe were introduced to the American mineral industries for the first time.

By 1890, it was believed by many that most of the country's copper deposits were known and explored. The next years were to witness startling developments in the search for new orebodies, however, and in the extraction and the refining of the metal to meet the insatiable demands of the rapidly growing electrical industry. A distinct change was noticeable about 1897 in the methods used for the extraction of the red metal from its ores.

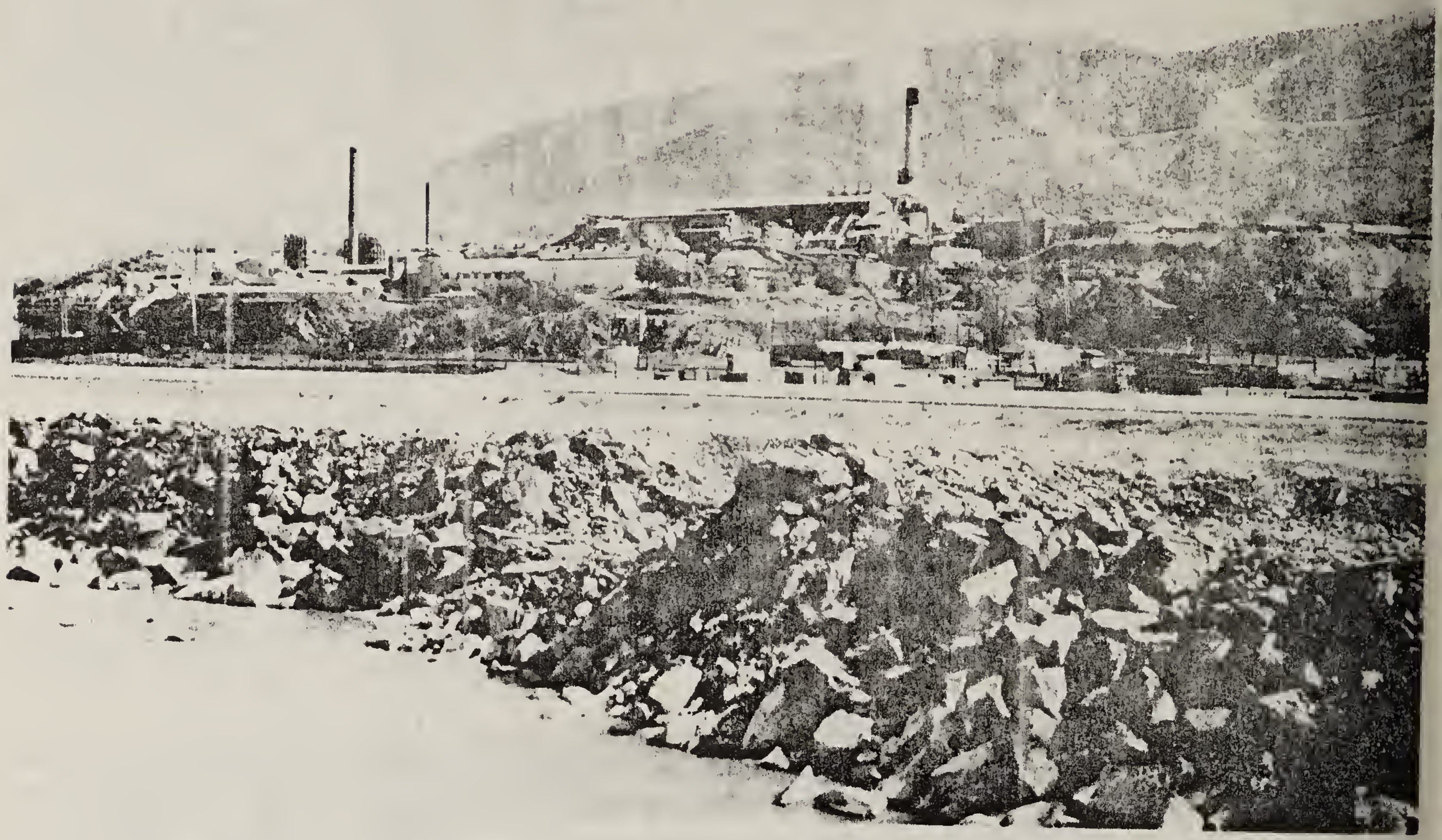


Fig. 40 - The plant of the Bunker Hill Company at Kellogg, Idaho, where differential flotation was developed to permit the separate concentration of lead and zinc ores. Froth flotation as a means of concentrating metallic sulfide minerals considerably enhanced the development of such mineral deposits in the West. Its introduction meant additional space requirements for beneficiation plants and a continued need for abundant water.

Many authorities were saying (no doubt having the decline of the native copper mines of Michigan in mind) that hardly any copper ore was so rich then as to be able to forego some concentrating process for the removal of waste.

For some years the domination of Swansea as the smelting capital of the metal world had been eroding away as American metallurgists worked out their own problems in their own way. Smelting also became the principal method of copper recovery in the American West. One of the oldest processes was that of *heap-roasting,* with its variations of *kennel-roasting* and *stall-roasting.* It was proved to be one of the cheapest ways of dealing with pyritic ores. It could also be used for ores carrying up to 15 percent sulfur by placing a large amount of burning wood under the pile of ore and mixing it with sawdust and charcoal. It must have been an impressive sight, 250 tons of ore in heaps 20 feet by 50 feet burning for ten weeks at a time, but the disadvantages were obvious. The heaps had to be large to be economical, the time consumed was excessive, and the burning had to be in the open so that much copper was lost either by leaching or by being blown away as fine dust. The introduction of large amounts of obnoxious gaseous waste into the atmosphere was not considered to be any particular disadvantage. The fact that those gases contained significant amounts of valuable metal that could not be recovered was a serious matter. The same was true with respect to the creation of copper-bearing liquid wastes. The possibility of polluting a stream or two in the vicinity of the heap-roasting operations was considered relatively inconsequential in the 1800's. The loss of copper in runoff solutions was of consequence, however, and was to be avoided.

More sophisticated equipment involving furnace smelting was quickly introduced to treat the copper sulfide ores developed after 1872. The reverberatory furnaces that were widely used in the 1870's and onwards were of three types, the Howell White, the Bruckner (the Anaconda smelter in Butte used 136 of these), and the Pearce turret furnace, used by the Boston Colorado Smelting Company in Denver. For treating copper mattes, the major process was *bessemerizing,* which consisted of utilizing the sulfur in the ore as a fuel for bringing the metal to a further stage of purity.

At Butte, the matte produced in the blast furnaces was left to get cold and solidify and then was broken up by sledges to pieces about the size of a man's fist. The broken matte was then charged into remelting furnaces which consisted of a simple cupola lined deeply with a mixture of crushed quartz and fire-clay that had been pounded hard. By these remelting processes and the use of a Bessemer converter, not only was the copper more refined but important by-products could be saved as well. These included bismuth, cobalt, gold, lead, manganese, nickel, silenium, silver, tin oxide, and arsenic. In many cases, however, in 1900 only the copper was saved, and the important by-products were wasted.[104]

The first copper smelting in Arizona was at the Longfellow Mine near Clifton, where at first a brick furnace was employed, the refractory bricks costing as much as a dollar apiece. Then another furnace was built out of crude copper plates, cast on the spot, and sprayed with cool water. In such an isolated locale the problems of smelting were enormous. Charcoal had to be hauled in by mule a distance of 100 miles from the Burro Mountains, and little progress could be made until the arrival of the railroad in 1880.

Arizona copper smelting of consequence really starts from that year. The Copper Queen smelter started up in 1880, and small operations at Globe and near Clifton followed a year later. The Copper Queen began with a small, 36-jacket furnace using Swansea and Cardiff coke imported via San Francisco. Not until later was it found that coke from Colorado and New Mexico was just as suitable. This was fortunate, since it was in 1893 that a Bessemer plant had to be ordered for Bisbee to handle the large reserves of sulfide ore that had been exposed.

In Colorado, the Boston and Colorado Smelting Company at its Argo works included a leaching process in its smelting operation, the residue from which contained a considerable amount of silver. This was re-smelted with auriferous pyrites (found in Gilpin County tailings) for the contained gold by a process that remained secret. At Butte, Montana, however, the Parrot Smelting Company used all of the methods that have been mentioned. Ores were roasted in stalls and on hearths with wood fuel at the same time that *Rachette furnaces* were coming into use. The latter passed on the ores to a remelting cupola and then into a converter, which concentrated the matte from 55 percent to 99.5 percent copper, after which it was shipped to a refinery at Bridgeport, Connecticut.[105]

By 1893, electrolytic methods were already on the way to ensuring the production of absolutely pure copper and, at the same time, allowing the extraction of the contained gold and silver. This gave electrolytic refining many advantages over refining by fire. Three main processes developed, in all of which the anodes were of blister copper and the electrolyte was a solution of copper sulfate. The only differences were in the arrangement of the electrodes and the lining of the wooden vats which held the copper sulfate solution. They were all restricted, of course, to using high-grade copper matte or blister copper containing 98 percent pure copper.

Smith's Process was used by the Electrolytic Copper Company of Ansonia, Connecticut, and by the Pennsylvania Salt Manufacturing Company of Philadelphia. The so-called *Multiple Process* was favored by a majority of the smelting firms, including the Balbach

Fig. 41 - Copper smelting in Arizona about 1898 employed basically the same processes as at present, but the early equipment was generally smaller and less complex. The smelting of metallic ores at the individual mining properties was relatively common in the late 1800's. (Photo courtesy of Arizona Pioneers' Historical Society)

Smelting and Refining Company of Newark, New Jersey, the Boston and Montana Consolidated Copper and Silver Mining Company of Great Falls, Montana, the Chicago Copper Refining Company of Blue Island, Illinois, Lewisohn Brothers of Pawtucket, Rhode Island, the Omaha and Grant Smelting Works of Omaha, Nebraska, and the St. Louis Smelting and Refining Company of Cheltenham, Missouri. *Hayden's Process* was employed by the Baltimore Copper and Rolling Company, the Baltimore Refining Company, the Bridgeport Copper Company, and the Anaconda Electrolytic Refining Company.[106]

In the late 1800's and the first two decades of this century, three basic processes for the treatment of copper ores were developed for different types of ores from different mining districts. The native-copper ores of Michigan responded readily to water-gravity concentration for the gravel and sand particle sizes and to froth flotation for the slimes. Sulfides were treated by flotation, and the oxides, carbonates, sulfates, and silicates responded best to leaching.

Direct smelting was generally used for high-grade ores containing upwards of six percent copper, while leaching, followed by electrolytic precipitation or precipitation by iron, was used for oxidized ores. Concentration followed by the smelting of the concentrate was used for low-grade sulfide and native metal ores. The sulfide concentrate was smelted in reverberatory furnaces, usually with prior roasting, forming a mixture of copper and iron sulfides (matte), which was drawn off molten and sent to a converter. There it was blown with air which oxidized the iron, causing it to slag off as a silicate, and afterwards oxidized the copper sulfide to crude metallic copper, which was subsequently refined electrolytically.

Generally all copper ores, except those containing the metal in sulfate or silicate form, were concentrated in one form or another. The advantages of smelting over either wet-processing or heap-roasting were enormous. A wet-plant using hydrometallurgical processes cost about four times as much as a smelting plant and occupied four times as much ground space, while the recovery rate was nowhere near as high. Nevertheless, solution methods were important in copper production from western ores in the last decades of the 19th Century. Used for the most part when the percentage of contained metal was very low, the process mostly favored in the West was the Hunt-Douglas, its first form having been patented as early as 1869. In this process, ferrous chloride was dissolved in strong brine and then was made to react on cupric oxide leading to a mixture of cupric and cuprous chlorides, which were then dissolved by sodium chloride. The dissolved iron was separated as hydrous ferric oxide, and the copper easily precipitated from these solutions by metallic iron.

By 1897 this process had undergone several modifications and improvements, and was used extensively by the Kansas City Smelting and Refining Company for extracting copper from silver-lead mattes. In most instances, a solution of common salt and ferrous chloride was made to attack oxidized copper ore. The ferrous chloride became decomposed, forming a clear solution separated from the ferric oxide but containing cupric and cuprous chloride. This was then treated with sulfurous gas to convert it into cuprous chloride with the separation of free acid. Any silver present in this acidic cuprous solution was easily precipitated by metallic iron.

The copper produced in this way was exceptionally pure for the time, although the consumption of iron was high. Production of 100 tons of copper would need as much as 88 tons of iron. The success of the process depended upon the copper solutions being run at speed over the iron. At Copperopolis, California, the saturated leach waters were conveyed to tanks from which they were discharged into drums, revolving at a speed of six revolutions a minute, that contained a charge of scrap sheet iron from San Francisco. *Cement copper* was formed in the drum, which was then shovelled out and dried out on heated drying floors. A similar method was used at Clifton and Morenci in Arizona. The leaching works had just been erected in 1893 to treat the tailings by sulfuric acid and iron to precipitate the copper, for, although the ores were rich in carbonates, the loss of copper in the tailings was heavy.

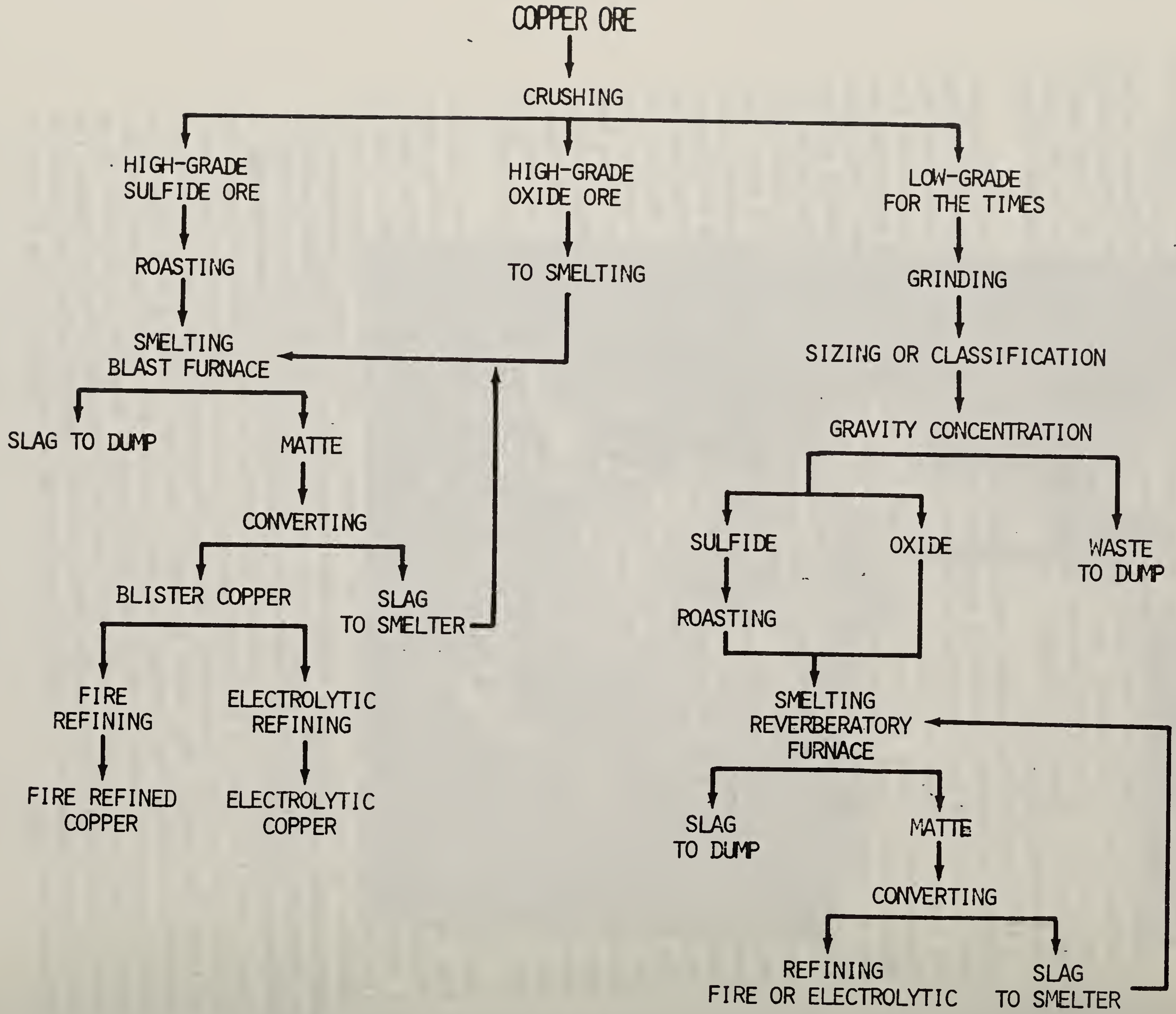


Fig. 42 - The extraction of copper from its ores before the introduction of froth flotation in the early 1900's involved basically the same metallurgical processes as today. Gravity concentration was used where

Table 27

COPPER PRODUCTION COSTS IN THE UNITED STATES, 1917-1935

Company	Estimated Cost of Producing Copper[a] (Cents per Pound)				
	1917	1920	1924	1929	1935
Anaconda (Montana)	9.19	8.16	8.32	b	6.8
Calumet & Hecla (Michigan)	8.85[c]	11.05[c]	10.19[c]	9.65	7.96
Copper Range (Michigan)	8.58[c]	9.23[c]	14.59[c]	12.16[c]	8.26[c]
Inspiration (Arizona)	7.08	7.37	8.96	9.65	32.66[d]
Kennecott (Alaska)	5.34	6.42	8.61	6.54[c]	6.4[e]
Magma (Arizona)	11.30	9.49	6.44	8.64	5.62
Miami (Arizona)	8.51	6.17	9.21	10.07	9.02
Mother Lode (California)	b	4.49	5.83	5.65[c]	4.57[f]
Phelps Dodge (Arizona)	9.02	7.94	9.99	10.40[c]	7.15[c]
Shattuck Den (Arizona)	9.01	12.20[c]	8.20	10.57	11.22
United Verde Extension (Arizona)	4.17	5.11	6.75[c]	7.13[c]	7.13
Utah (Utah)	7.49	6.82	7.24	5.58	7.50
Walker[g] (Canada)	b	b	b	9.06	10.98
Granby (Canada)	9.49[c]	8.27[c]	8.64[c]	8.44	8.82

[a] adjusted to purchasing power of 1935 dollar after depreciation and all credits, except where noted

[b] not estimated

[c] no depreciation

[d] charging shutdown and other expenses against two new operations

[e] cost per pound crediting fabricating operations

[f] including depletion, no depreciation

[g] cost per pound of copper in concentrates

Source of data: J. J. Croston, *AIME, Transactions,* Vol. 126, 1937.

Table 28

COPPER PRODUCTION IN THE UNITED STATES
1936-1947

Year	Production		Average Grade of Ore (percent copper)		Open Pit Production		Open Pit Productivit	
	Total ore (1,000 tons)	Total copper (1,000 tons)	All mines	Open pits	Percent of total ore	Percent of total copper	Tons of ore per Man/hr[a]	Pounds of copper per Man/hr[a]
1936	38,514	614.5	1.60	NA	63	NA	4.98	NA
1937	61,513	842.0	1.37	NA	60	NA	4.68	NA
1938	37,795	557.8	1.48	NA	54	NA	3.36	NA
1939	55,239	728.3	1.32	.92	59	41	4.15	76
1940	69,279	878.1	1.27	.91	61	44	5.00	91
1941	78,453	958.1	1.22	.91	63	47	3.44	62
1942	92,286	1,080.0	1.17	.90	66	51	3.76	68
1943	98,120	1,090.8	1.11	.87	69	54	4.80	83
1944	91,064	972.5	1.07	.90	68	57	5.24	94
1945	77,473	772.9	1.00	.89	68	61	4.90	87
1946	62,232	608.7	0.98	.86	66	58	5.08	87
1947	87,865	847.6	0.96	.90	73	68	5.00	90

[a] Includes open pit employees only.
NA Data not available.

Source of data: *Minerals Yearbook* and other Bureau of Mines sources.

10. Changes in the Advanced Processing of Gold

Developments in hydrometallurgy in the late 19th Century were also important in other metals. Evidence has been found indicating some hydrometallurgical processes were in existence before 1550 A. D.,[107] but the principal processes used in the late 1880's and early 1900's include those which treated gold, silver, and copper.[108] While the first large-scale leaching and precipitation of copper was probably done at Rio Tinto in Spain about 1752,[109] and gold and silver were leached from their ores prior to 1887, the chief credit in proving the adaptability of cyanide to gold ore and in putting before the world a workable process for gold extraction is due to J. S. MacArthur, R. W. Forrest, their colleagues, and the Cassel Gold Extracting Company of Glasgow, Scotland. MacArthur and Forrest's patents were applied for in Great Britain in 1887 and 1888.[110]

The history of the technology for the recovery of gold is perhaps one of the longest and most complex, being rivalled only by those for silver and copper. At the very beginning, it is likely that no more was done than hand pick auriferous rock and roast it in some crude furnace to get rid of the excess of arsenides and pyrites. But by 1860 it had become more common to reduce the ore in size by subjecting it to some form of jaw-crusher and then to a set of steel rolls, if dry-crushing had been decided on. The *Mining and Scientific Press* of September 8, 1860, made much of a device called *Mill's Crushing Machine*, that consisted of a series of circular rollers of solid iron. The ore passed through a hopper at one end and so through the rollers. It was claimed to be so effective, rather optimistically no doubt, "that sieves can be dispensed with," and that it could work wet or dry.

Dry-crushing was never as acceptable as wet-crushing, and in wet-crushing the heart of the size reduction process was the *gravity stamp mill,* consisting of a series of pillars actuated by cams mounted on a revolving shaft. The feet of these pillars were shod with massive shoes of iron, and the mill pounded the ore into a battery or trough. The importance of the stamp mill lay in the fact that it was both a reducing and amalgamating plant. The ore, the mercury, and the water were all pulped into what were called slimes, ready for extraction. In a series of articles in *The Engineering and Mining Journal* of 1895, T. A. Rickard concluded that, whatever the refinements over the years, one feature of the stamp mill stood out clearly against all other forms of pulverizers. It was both a crushing and amalgamating, a size reducing, and an extracting machine combined. The steam-stamp might be a superior crushing machine, he observed, but its violence of agitation prevented the introduction of amalgamating plates, thus failing to provide the conditions for successful gold milling.

Even so, the stamp mill was not completely successful, for much gold was lost in the slimes, and even the introduction of mechanical paddles to stir the pulp in the mill was not much of an improvement. This was always the problem of gravity separation, even on the bumping and shaking tables and in the amalgamating pans where the final concentrating took place. In 1897 a favorite gold processing arrangement was known as a 30-head gold milling plant. It consisted of two turbines, two ore-breakers with steel jaws, 30-head of stamps, six amalgamating pans, all lodged in an iron house, 60 feet by 30 feet, with wrought-iron columns and strong foundation plates, complete with offices, a retort house, and an amalgamating room.

Chlorination for a time was thought to be the answer to the problem of recovery of the values lost in milling and to be especially suitable for rich gold-bearing sulfides. It had considerable vogue in the last quarter or so of the 19th Century, but was abandoned because of the arrival of the more successful *flotation* and *cyanidation* processes.

Rickard, in an article in *The Engineering and Mining Journal* of October 19, 1895, "Variations in the Milling of Gold," claimed that the chlorination process was first employed at Grass Valley as early as 1857. While he did not elaborate on its origins, Rickard presumably meant that at that time it was a well-known fact that gold would react with chlorine in the form of bleaching powder to produce a soluble gold chloride which could then be reduced by means of precipitation. Nevertheless, it took another forty years to arrive at the barrel process, in which the gold-bearing concentrates were first roasted in a calcining furnace and then, after being slightly moistened, were shovelled into revolving lead barrels into which chlorine gas was induced. After about four hours or so, the chemical action produced a soluble chloride of gold, which was then washed through filters and the gold subsequently precipitated.

During its brief life, the chlorination process underwent several improvements. Yet the method had many disadvantages that would have proved its own undoing. The chemical reaction was rather slow. A tremendous storage capacity for the chlorine gas was required and it needed to be gas-tight, which meant that it was costly to build and maintain. Bleaching powder was expensive and chlorine gas was dangerous, but most important of all, it was found that other metals in the charge reacted before the gold did, thus causing further expensive treatment of the resulting solution. Furthermore, the recovery of the gold was not all that great, and certainly not large enough to justify so costly an operation.

Chlorination had hardly become established before it was superceded by froth flotation and cyanidation. The principle of flotation was based on the knowledge in circulation for many years that water can be displaced by certain oils at the surfaces of certain mineral particles. Everson, in 1886, described the use of sulfonated fatty oil with inorganic acids and the introduction of air by agitation to effect the levitation of metalliferous sulfides and oxides,[111] and apparently an experimental plant was set up in Denver as early as 1889.[112]

The antecedents of the *cyanide process* were many, and accounts of its development are confused. The fact that gold could be dissolved in a solution of potassium cyanide seems to have been known in Germany as early as 1805, while Faraday described how he did this experimentally in England in the *Transactions of the Philosophical Society* of 1857. Apparently in 1867, one Julio H. Rae of Syracuse, New York, took out a patent for treating auriferous ores in this way, and others followed his line, but no effort seems to have been made to introduce their findings into the field of metallurgy.

It was not until 20 years later that three Scots chemists took out an English patent for the recovery of gold by the use of a dilute solution of potassium cyanide, the use of zinc as a precipitate, and the use of caustic alkalis for neutralizing acid ore. The fact that their methods were not really new sparked in a whole series of legal battles and law suits over the validity of their patent rights. Nevertheless, their process ushered in a revolutionary period for the recovery of gold from the mountains of tailings.

In the 1890's the cyanide process involved a strong solution of potassium cyanide which was made in a tank and run off through a finely-woven steel wire filter into storage tanks, where it was diluted until its strength was as low as 0.3 or 0.6 percent. This solution was then passed into leaching vats filled almost to the top with the tailings that required treatment and was allowed to percolate through the mass. The resulting solution was drawn off and run through precipitating tanks (or zinc boxes) which contained zinc shavings, on which the gold was precipitated. The mixture of zinc and gold was then retorted, the zinc volatizing itself, and leaving the gold. The plant required for this method was not particularly expensive in that all that was required were tanks for dissolving, storage, leaching, and precipitating. These could be supplied by manufacturers and, for convenience, could be mounted on bogies for easy transport on tracks to the location of the tailings to be worked. For the individual cyanider, who proceeded to attack every available mound of tailings, there was even a portable cyanide plant.

Although cyaniding had come into wide use for gold processing by 1900, *amalgamation* continued to be employed throughout the West. For separating the precious metals from their ores by mercury, a number of devices were used both before and after the early 1900's. One method involved stamp mills with amalgamated plates placed inside. As the gold ore was being crushed and ground, the free metal would spatter and adhere to the mercury-coated plates, forming an amalgam. In another process, crushing and grinding devices would mix mercury with the ore as it was ground, and the free gold would thus amalgamate with the mercury. Another method involving mercury-coated plates saw crushed and ground ore in the form of pulp fed over or through different devices which held mercury-coated plates to which the free gold would adhere.

Other processes were also developed to produce gold (and sometimes silver) amalgams. Mercury wells collected free gold as the pulp was passed through or came in contact with a pool of mercury. In some methods, mechanical amalgamators brought crushed and ground ore carrying free gold into contact with the mercury by some mechanical scouring process.

Mercury thus remained important for many years in the extraction processes used in recovering gold from its ores. The processes used to recover mercury itself did not change appreciably during the period from 1872 to 1947, although some modifications were made in the basic retorting system. At times, the recovery of mercury from gold-processing operations received as much attention as did the recovery of the metal from cinnabar, its common ore mineral. In fact, in the 1920's and after, there was a massive clean-up at some mines to recover the mercury that had drained into the ground and become lodged in flues and chimneys.

11. Changes in Silver, Lead, and Zinc Extraction

Changes in the advanced processes used in producing silver, lead, and zinc ran between the changes that occurred in gold and copper. In many cases the methods were almost identical because of the high affinity of these metals for each other in many western mineral deposits.

In the period from 1872 to 1947, lead and zinc were usually found in association with each other and therefore presented complex problems of both concentrating and smelting. Only rarely were they found to occur separately. For the concentrating of the purely lead ores, the practice followed by the St. Joseph Lead Company at Bonne Terre, Missouri, seems to have been typical for the 1890's. First, the ore was crushed by jaw-crushers and rolls and screened dry. The sands passing through the screens were mixed thoroughly with water and elevated by centrifugal pumps to distributors and then divided among Parson jigs without regard to size or classification. The hutchwork that came through the jigs then passed through a series of pyramidal boxes. The heavy galena, mixed with some sand and slime, settled in the first box, from which it was fed into a trunking machine and then on to the smelting works. Tails from the trunking machine, together with the sands that had settled in the second box, were elevated again by centrifugal pumps and divided between jigs. The fine slimes that settled in the third and fourth boxes were mixed and again raised by pumps to the distributors feeding a row of vibrating tables producing an added amount of concentrate.[113]

The smelting of lead was particularly difficult since it was all too often a constituent of silver-bearing ores, and in the 1890's the main occupation of lead smelter metallurgists was to find solutions to the problem of silver-lead separation. Experimentation was quite extensive.

Apparently the lead smelting furnace most favored in America was the four-hearth furnace, so-called because the length of the hearth was roughly four times its width and no step marked the division of the hearths. Capable of smelting about ten tons of ore a day, its essential feature was a fusion hearth, almost circular in shape, beneath which was situated the calcining vaults that took the ore charge. Many improvements and sophistications were suggested, but by and large the western smelters continued to prefer this long double-hearth reverberatory furnace.

After this primary roasting process, most lead ore still had to undergo a further refining, for generally it still contained (in addition to silver) some antimony, arsenic, copper, iron, and zinc in amounts sufficient to hinder the final recovery of the silver. The method used for further refining was to melt the crude lead and expose it to the oxidizing influence of the atmosphere until all the impurities were recovered as surface scum, thus leaving a pure silver-lead alloy. The final extraction of the silver from the lead-silver alloy was accomplished by cupelling it, i.e., by causing a rapid oxidization of the lead without affecting the silver.

What to do with the slag was always a problem in lead smelting, for it might contain as much as one percent lead and one ounce of silver per ton and therefore be worth re-smelting. At Leadville, Colorado, the practice was to use an old furnace for this purpose, the rich slag there averaging more than five ounces of silver per ton.

As the lead mines reached greater depths and the oxidized surface ores became exhausted, the treatment of zinc-lead sulfides became of increasing importance, and even by 1900 the problems of smelting such ores had really not been solved. Some success had been attained at the works of the Picher Lead Company at Joplin, Missouri, by employing what was known as the Lewis-Bartlett process, in which the smelting was aimed directly at the volatization of the zinc. Special means were adopted for catching the zinc oxide and lead sulfate fumes, while the residual matter and slag contained iron, some lead, and most of the silver from the original ore. These were then charged in an ordinary lead-smelting furnace. The same process was used at Canon City, Colorado, for the argentiferous zinc-lead sulfides treated there.

Elsewhere, what was called the *West Process* was being tried out with some success in 1893 at the Silver Valley Mine in North Carolina. This operation involved a long series of unit processes: (1) roasting the ore; (2) cooling it; (3) moistening it with water; (4) placing it on a layer of pebbles in a false-bottomed tank; (5) forcing the sulfurous acid from the roaster with a jet of steam through the ore in the tank, and thus converting the oxide into sulfite and ultimately sulfate; (6) removing the ore to a separate tank; (7) leaching it with water; (8) passing gaseous ammonia into the solution, thus precipitating zinc hydrate; (9) transferring the solution of ammonia sulfate to a still; (10) adding lime and heat to regenerate the ammonia; (11) drying the leached ore containing the iron, lead, and precious metals on an iron floor heated by the roaster; and then (12) smelting it in the usual way. The process, however, was considered to be too complicated and costly for wide application and at best recovered only 80 percent of the lead and 70 percent of the zinc in the concentrate.[114]

In 1895 there were some remarkable zinc deposits being worked that were entirely free of lead. At Saucon Valley, Pennsylvania, three principal mines, the Ueberroth, the Hartman, and the Saucon, all were on a belt of zinc nearly a mile in length. At Franklin and Sterling Hill, New Jersey, an enormous bed of zinc ore, 2,500 feet long and about 30 feet in width, was being mined down to a depth of 200 feet. In Upper Mississippi, the lead regions were extensive shallow deposits of "dry-bone," that is, *smithsonite* or zinc carbonate. Near Butte, Montana, was the Gagnon vein of rich zinc-blende (*sphalerite*), thousands of tons of which were being smelted at Argo, Colorado. In Virginia, there were several zinc mines near Wythe City, and there were also valuable zinc deposits in Southwestern New Mexico.

For the treatment of zinc, the process developed at the Bertha works in Virginia about 1895 may be regarded as typical. There, the storage bins for receiving the ore as it came from the mines were provided with a water-carriage system. These bins consisted of timbered trestles, built out from a hillside and provided with V-shaped floors, down the center of which passed the water trough. When the ore had been dumped, it was fed regularly into the water trough and then carried by the action of the water to the dressing-house 1,300 feet below.

The water was pumped up from the river by heavy Worthington pumps to a large tank at the top of the hill and from there fell by gravity into the flumes which were made of cast iron. From the flumes, the zinc ore fell onto a grizzly and the smaller lumps passed into a single revolving log-washer, which gave it a gentle primary sluicing to separate and dissolve the clay and "buckfat." The lumps were then crushed by a jaw-crusher and a pair of Cornish rolls and sorted for size by a conical, perforated, and revolving screen. The smaller pieces passed down to four sets of jigs on which they were thoroughly concentrated. While the tailings still had to pass through a classifier and then over two other jigs, the concentrated ore was dried in a roasting plant and then shipped to the smelter.

The Bertha smelting works consisted of ten large Welsh-Belgian furnaces, each containing 140 retorts or pots. The calcined ore, mixed with a proper proportion of anthracite coal, was charged into the retorts, a short clay condenser being set into the mouth of each. The furnaces were fired from below, the flames circulating around and between the pots causing the reduction of the zinc ore by combining the carbon of the coal with the oxygen of the ore.[115]

A different practice had to be followed for the Wisconsin-Illinois zinc deposits because they were scattered and small. As a result, it became the habit to erect small mills at the mouth of each pit, treat the rough ore by gravity concentration on jigs, and then sell the concentrate to central cleaning mills which also specialized in roasting and magnetic separation.

For complex ores, a great many plants adopted the same procedures, tinged with local varieties. For example, at the Bunker Hill and Sullivan Mining and Concentrating plant in Northern Idaho, the concentration began with the usual crushing and finished with a simple lead-zinc differential flotation. The plant of the Anaconda Copper Company in Montana was much the same. There, jaw-crushers with scalping screens were followed by rolls, and the size reduction was followed by flotation which was followed by cleaning. The depression of the zinc concentrate during flotation was obtained by using zinc sulfate and sodium cyanide. Most of the zinc concentrates from the Coeur d'Alene were shipped elsewhere for smelting. Only in 1928 did the Bunker Hill Company start its zinc reduction plant. [116]

12. Changes in the Advanced Processing of Ferrous Metals

While the development of processes for the advanced treatment of the ores of nonferrous metals accelerated after 1872, the processes for the production of iron from its ores underwent little fundamental change until after the middle of the 20th Century. Nevertheless, if the methods of concentration were relatively simple, never was a field of technology more exposed to inventions as was the smelting of iron. Yet the general principle followed was much the same, using furnaces where the charge was subjected to continuous blasts of heated air. Furnaces were fed with ore mixed with coal and limestone as a purifier or flux for the removal of the earthy matter from the ore. The molten metal, being the heaviest component of the charge, was drained to the bottom of the furnace, from where it was drawn off into moulds or pigs.

The conversion of pig iron into malleable iron, necessary because the pig iron contained too much carbon, was achieved by oxidation in a puddling furnace. The oxygen was derived from iron peroxide provided in the *fettling* used for the lining of the furnace.

The next stage was to convert the malleable iron into steel. This was done by heating it with charcoal in a *cementation* furnace. This intermediate stage was subsequently avoided with the appearance of the open-hearth or reverberatory furnace, by which it became possible to go straight from pig iron to steel. An important refinement in open-hearth converting was subsequently to eliminate the phosphorus in the pig iron by using a basic instead of a siliceous lining in the converter, incidentally producing a most valuable fertilizer that contained 25 percent phosphoric acid as a by-product.

The by-products of the iron industry attracted continuous and considerable attention after 1900, since some means had to be found to get rid of the millions of tons of slag that began to cover the land. The manufacture of fertilizers became by far the most important, but the use of slag in the cement industry also developed. The discovery that puddle-slag could be used in the paint industry if mixed with heated cinders after being crushed to a fine powder in pulverizers and settled in air chambers (a process worked out at Boonton, New Jersey) also helped to utilize some of the waste products of the iron- and steel-making process.

Methods for the advanced treatment of most ferro-alloy ores did not appear until after 1900. None of the steel-making uses, of course, was thought of in the 1890's when molybdenum was first being talked about. The report, *The Mineral Industry, Its Statistics, Technology, and Trade, in the U. S. and Other Countries from the Earliest Times to the End of 1892*, described the metal as being used in the form of molybdic acid as a chemical reagent and as molybdate of sodium to produce a strong, solid, and brilliant blue in the pottery industry and for the coloring of woolens. But it also added: "Although the compounds of molybdenum have some important uses in the arts, the quantity of them required is small and there is no great demand for the mineral." It was suggested that if the demand were to increase, the metal could be supplied in very large quantities since it was said that considerable deposits existed among the mountains of Virginia, in the Adirondack region of New York, at Blue Hill Bay, Maine, at Westmoreland in New Hampshire, and four miles north of Pitkin near Rock Creek, Gunnison County, Colorado, where the ore existed "in sufficient quantities to make the deposits valuable if ever there is a market for it."

At the same time it was being noticed that experiments were afoot to use molybdenum in an alloy with steel, the object being to obtain a product as hard as tungsten steel and at the same time more malleable and less brittle. It was, of course, this development that made the deposits in Colorado of prime importance. The nation's center of molybdenum production since 1920 has been at Climax, Colorado, where the molybdenite is mined from a large disseminated deposit.

Table 29

IRON ORE PRODUCTION IN THE UNITED STATES
1936-1947

	Production		Average	Productivity[a]		Open Pit	
Year	Crude ore (1,000 long tons)	Contained iron, (1,000 long tons)	Grade (percent iron contained)	Crude ore tons per man/hr	Contained Iron tons per man/hr	Production (Percent of total ore)	Productivity long tons per man/hr
1936	54,856	24,684	45.0	1.47	.66	67.3	7.6
1937	80,906	36,411	45.0	1.57	.71	71.0	7.3
1938	31,718	14,094	44.4	1.04	.46	56.8	2.9
1939	57,353	26,012	45.4	1.47	.67	66.8	4.9
1940	83,404	37,316	44.7	1.71	.77	71.0	7.0
1941	107,720	47,060	43.7	1.78	.78	74.7	5.6
1942	126,527	53,489	42.3	1.68	.71	73.3	5.7
1943	119,675	51,299	42.9	1.56	.67	72.6	6.2
1944	112,255	47,982	42.7	1.71	.73	74.2	7.0
1945	107,509	45,662	42.5	1.77	.75	74.0	7.4
1946	85,152	35,491	42.2	1.70	.72	75.9	8.0
1947	114,899	47,000	40.9	1.77	.73	75.1	6.7

[a] Includes surface and underground employees, shops, and preparation plants.

[b] Includes surface mining employees only.

Source of data: *Minerals Yearbook* and other Bureau of Mines sources.

The treatment of other ferro-alloys also began in earnest after 1900 even though the development of their mining remained dormant in the United States. The domestic mining of nickel, for example, never has been of great consequence. In 1892, scattered deposits were reported as existing in Arkansas, Colorado, Connecticut, Iowa, Massachusetts, Missouri, Nevada, North Carolina, and Oregon, but up to 1893 the chief source of supply was the Lancaster Gap Mine in Pennsylvania. By the end of 1894, however, this mine was almost exhausted, exploration work had revealed no new orebodies, and production was limited to "picking out the eyes" of old stopes. It is true that the lead mines of Southeast Missouri turned out a small amount of nickel-cobalt *speiss* as a by-product, but their concentrates had to be sent to England for treatment. Oregon and Nevada showed some slight promise but returned no marketable yields, though it was reported in 1894 that the National Nickel Company of New York was contemplating the erection of a matte smelting works at their mines in Nevada.

Nickel smelting, however, was well advanced by the end of the 19th Century, mainly through the efforts of several firms on the East Coast, namely the American Nickel Company at Camden, New Jersey, the Canadian Copper Company, near Cleveland, Ohio, and the Oxford Copper Company at Constable Hook, New Jersey. All of these companies were refining Canadian matte and producing nickel oxide for the refining of steel by 1900.

The Oxford Copper Company was particularly successful and by its fire process was instrumental in making a metallic nickel that was 99.3 percent pure. In 1894 it was also experimenting with an electrolytic process that could produce nickel for use in the manufacture of German silver, and this turned out to be of so remarkable a purity that it was even in demand throughout Europe.[117]

13. Changes in the Advanced Processing of Other Metals

Another metal that did not come into prominence until after the turn of the century was *aluminum.* Like nickel, its advanced processing methods were developed in the United States even though there were only limited amounts of aluminum-bearing ores produced by domestic mines. The metal is widely distributed as a constituent of many different minerals, but extraction was and is only commercially feasible from bauxite or cryolite. The known American deposits were in Alabama, Arkansas, the Carolinas, Georgia, Tennessee, and Virginia, but they were limited in size and quality.

The significance of *uranium* in the industrial and political world of 1968 does not need any underlining, but in 1893 it was being remarked in *The Mineral Industry* (1893) of that year (p. 572) that,

> There is no use for metallic uranium, but its salts are valuable in the arts, being employed in the manufacture of uranium glass, which has a peculiar yellow colour, with a greenish reflex, which is much admired. They are also used in colouring porcelain and to some extent in photography . . . If uranium could be found in larger quantities, there is no doubt that it would find a more extensive use in the arts.

At the time, some English and German metallurgists indeed were looking for uses very far removed from the arts, believing that it could increase the elasticity and hardness of steel and hence be of tremendous value in the making of guns and armor plating, all part of the growing anxiety about the new military power of post-1870 Germany. It was felt by many, however, that the high cost of uranium at the time precluded its employment for that purpose. According to Lock, the market price in 1895 was roughly equivalent to four dollars a pound.

About 1891 pitchblende was found among the rocks of the Ball Mountain district in the Black Hills of South Dakota, but as early as 1871 Pearce had come across a lode in the Wood Lode Mine in the Russel district of Gilpin County, Colorado. In view of the fact that it is in the same area that uranium discoveries were made after the end of World War II, what the original discoverer had to say is worth noting:

> The mine had been abandoned . . . When unwatered the shaft was found to be about 100 feet deep, and I discovered that at 60 feet from the surface a body of pitchblende had been passed through. On further development its dimensions were found to be 30 feet long and 10 feet deep. The vein of ore was about 10 inches thick. Nearly four tons of it, carrying 70 percent oxide of uranium, were obtained. The former owners had sent the best part of the deposit to the stamps mill with their ordinary gold quartz. Complaint was made of the hindrance which the heavy black mineral offered to amalgamating but, being ignorant of its value, it was washed away with the water that flowed into the creek. Further search for another body of pitchblende proved unsatisfactory. A small bunch of this mineral, however, was found in the vicinity, at the Alps mine, on Quartz Hill.[118]

In 1939 these ores yielded almost 60,000 pounds of uranium, yet one minerals processing authority in 1944 was still saying, with justification, that "its uses are practically limited to the glass and ceramic industries" and that "the world potential resources of uranium considerably exceeds the present demands."[119]

14. Changes in the Advanced Processing of Industrial Minerals

The treatment of industrial minerals underwent considerable change after 1872, as increasing industrialization in the United States created new demands for chemical raw materials and a growing population required more minerals for fertilizers and construction materials. In 1892 the nation's most important phosphate deposits were in South Carolina, and some estimates placed known reserves at 14 million tons.[120] Actually, river mining there in 1891 extracted about half a million tons, and this rate of production was maintained until 1893 when an August hurricane practically destroyed the industry. After this, and as a result of it, there was an immediate demand for the Florida phosphate deposits while the search for new sources went on successfully in Tennessee.

In Florida an unusual method of mining the pebble phosphate deposits was in operation in 1895. A main rail line leading from the washers miles away was laid so that it divided the field of phosphate rock into equal parts on either side. Alternate laterals were then laid out at right angles, about 600 feet apart, and subdivided by a ditch. At the ditch, two workmen started their line of digging, equipped with no more than spades, shovels, and picks. Working in opposite directions, they excavated an area 300 feet by 12 feet. The rock that they dug out was then wheeled in barrows to a platform at the end of the road, where it was found that, by placing a pump under the banks, the latter could be made to cave in and the overburden drawn off through the pump, after which the pebbles could be handled and carted away. In some places, dredges were used to mine the rock that was in deep water, while *grappler dredges* were designed to cope with especially difficult rock.

From these early strip mines the rock was carried to the washers in dump cars. The washers were always located near deep streams, not only on account of easy shipment, but because of the colossal amount of debris carried off in the washing.

The beneficiation and processing system was relatively simple. The loaded cars were first hauled up inclines and their contents dumped into breakers. The crushers reduced the rock to particles about fist-size which then fell into circular troughs about 25 feet long. In each trough was an octagonal shaft, cased with iron and set with blades in such a way as to form a screw system which forced the rocks uphill and tumbled them all together. A heavy stream of water poured into the trough and washed the rock, at the same time pushing the rock upon screens of one-half inch mesh. Later, the rock was further sized on an oscillating wire table. The final operation involved drying the particles, either in the open air or, as was more often the case, by means of a Sturtevant fan dryer revolving at 2,000 revolutions per minute and drawing air through a woodburning furnace and into pipes inside a drying bin.

After 1900, although the pebble phosphates of Florida showed little signs of diminishing, those of Tennessee came into their own and new deposits were found in Idaho and the Mountain West. The treatment at first applied to the Western phosphates was that of log-washing with high-pressure sprays with the screening and discarding of all large material. Later developments made the processes much more efficient. Froth flotation eventually allowed recovery of about 80 percent of the phosphate in the washer fines.

The term *asbestos* was originally applied to the fibrous variety of the mineral hornblende (which was of no great economic importance) and then to fibrous serpentine or chrysotile, which now forms the bulk of the world's supply. Italian asbestos was the only known kind until deposits were found in 1878 in Canada, along the line of the Quebec Central Railroad from Quebec to Sherbrooke. There the mining was carried on in open quarries. After the rock was blasted, the long-fibred asbestos was knocked off the serpentine and the product of this simple operation packed in bags for delivery to the buyers, who would sell it for use in the packing of steam boilers and hotwater pipes and for fire-proofing.

Some asbestos deposits had been found in the United States by 1900, but they were generally so deficient in quality that they could not be profitably worked and were only of mineralogical interest.[121] In 1894 the only deposit of any significance was in White County, Georgia, where an asbestos mine was worked by the Sall Mountain Asbestos Company. There, two pulverizers were built with a capacity of 75 tons per day, and other machinery was installed for separating the fibres and packing them for shipment. The United States still had to depend on Canadian supplies for most of its asbestos, even though just before World War II, Vermont was producing about 12,000 tons annually.

The varieties of *limestone* seem to be as numerous as its occurrences, for it has been found almost all over the United States. One of the most useful of building stones, in 1893 the most popular was the oolitic limestone of Lower Carboniferous age found in the Central Mississippi Valley. Quarried extensively near Bedford, Indiana, and known therefore as Bedford stone, it was also worked in Illinois, Kentucky, Iowa, Missouri, and Arkansas. A less widely known, but equally valuable, stone was dolomite or magnesian limestone (called "cotton-rock" in some localities) of Lower Silurian age, occurring in Arkansas, Missouri, Iowa, and Minnesota, and another was the Niagara limestone of Upper Silurian age, found in New York, Ohio, Indiana, Illinois, and Arkansas. Also widely used were the Devonian limestones of New York, Iowa, and Minnesota, the carboniferous limestones of the Rockies, the tertiary *coquina* of Florida, and the white limestones of Alabama.

Limestone's early uses were likewise almost as numerous as its occurrences. By 1900 it was appearing as an important raw material in the manufacture of portland cement, bricks, glass, and paving blocks. It was considered ideal for railroad ballast and for macadamizing roads. Almost all curbstones, sewer caps, and flagstones were of limestone. Large quantities were bought for the making of carbonic acid gas for soda-water fountains, and ever vaster quantities were burnt in kilns to make agricultural lime.[122]

The techniques used in the winning of the limestone were simple at first and did not change much over the years. Lime burning was a widespread industry in the 19th Century as it had been in Europe for centuries before. A typical lime kiln in the California of 1895 was constructed in the form of a circular furnace about 60 feet high, tapering from a circumference of about 100 feet at the base to about 40 feet at the top, surmounted by a 60-foot stack. The kiln had an outer wall of ordinary brick and an inner wall of firebrick. The intervening space was filled with concrete so that all together formed a wall six feet thick.

The limestone to be burned was lowered to a charging platform which led to the door of the kiln. About 20 feet beneath this charging platform, the kiln was surrounded by a firing floor, on a level with which were three fireplaces, built at equal distances in the main body of the kiln. The ash-pits beneath the grates of the fireplaces extended directly down through the wall of the kiln, leading separately and directly to the ground or drawing floor, about 20 feet below.

The space in the kiln between the level of the fireplaces and the ground floor constituted a cooling chamber. The kiln was charged by filling this cooling chamber with waste rock up to the level of the fireplaces. The fires were then lighted with four-foot sticks of redwood and left to burn for three days. At the end of that time a charge equal to 24 barrels of waste rock was drawn from the bottom of the kiln and fresh limestone added at the charging door. After six drawings in 24 hours, the waste rock was all drawn out and the lime then began to make its appearance. This was then shovelled out, sorted, and made ready for shipment. A kiln of this kind could produce about 160 barrels of lime in 24 hours.[123]

The techniques used in treating limestone remained relatively simple after 1900. Initially broken by blasting, the cutting for dimension stone was chiefly done by gang saws, which consisted of soft-iron blades set in a reciprocating frame and fed with sand or a steel abrasive. Subsequent cutting was done with a diamond- or carborundum-toothed circular saw. Smoothing was achieved by planers or on a rubbing bed, a flat rotating cast-iron table. Crushing for broken stone, agricultural stone, and limestone dust was generally done through jaw-crushers and gyratories, standard cone crushers, rolls, hammer mills, revolving

Table 30

MINING AND BENEFICIATION COSTS, BAGDAD COPPER MINE, 1943

Mining	Labor	Supplies	Power	Miscellaneous	Total	Cost per ton
Stope preparation	—	—	—	$ 9,070.89	$ 9,070.89	$0.237
Drawing and tramming	$12,576.10	$2,805.60	$ 84.37	30.00	15,496.07	0.405
Maintenance	1,241.13	60.00	—	—	1,301.80	0.034
Hoisting	1,740.98	207.90	162.50	—	2,061.38	0.054
Pumping	6.82	64.55	30.80	—	102.17	0.003
Ventilation	13.64	52.86	42.64	—	159.14	0.004
Proportion of general	—	—	—	8,187.76	8,187.76	0.214
Total	$15,578.67	$3,191.58	$320.31	$17,288.65	$36,379.21	$0.951

Milling	Labor	Supplies	Parts	Power	Miscellaneous	Total	Cost per ton
Crushing	$1,134.51	$ 493.48	$489.91	$ 211.60	—	$ 2,329.50	$0.061
Ball mills	774.26	5,311.05	661.44	1,468.05	—	8,214.80	0.215
Flotation, copper	720.03	1,512.00	618.16	432.72	—	3,282.91	0.086
Flotation, moly	1,095.56	558.52	464.02	55.28	—	2,173.38	0.057
Filtering	917.73	22.17	145.72	78.63	—	1,144.25	0.029
Tailings disposal	1,380.68	19.19	236.34	—	—	2,136.21	0.056
Water	921.44	304.86	24.56	500.39	—	1,751.25	0.045
Proportion of general	—	—	—	—	$4,371.19	4,371.19	0.114
Total	$6,944.21	$8,201.27	$3,190.15	$2,746.67	$4,371.19	$25,403.49	0.662
Cost per ton	$0.118	$0.214	$0.081	$0.072	$0.114	$0.662	

Source: S. D. Woodruff, *Methods of Working Coal and Metal Mines,* New York: Pergamon Press, 1966, Vol. 3, p. 333.

screens, vibrating screens, and bar grizzlies. Washing was done by fishtail sprays over screens and by log-washers and blade mills to break up any tough clay.

The techniques changed in burning lime, however, with rotary kilns, adapted from cement practice. These were at first used for burning the spalls or fines and the firing was usually by gas, oil, or powdered solid fuel. Subsequently, and by 1947, rotary kilns were in virtually universal use for calcining limestone and similar industrial minerals.

The many technological changes that took place in the nonfuel mineral industries of the United States between 1872 and 1947 had many effects. The most noticeable was on labor productivity and consequently on the cost of minerals production. Although the unit price of labor was higher in 1947 than in the 1870's, the cost of producing a ton of ore had declined substantially. Total mineral output per man employed in the industry was much higher.

The productivity of other than human resources, however, had decreased by 1947. Minerals mined in most cases were considerably lower in valuable content than were those produced in the 1860's and 1870's. The vastly increased use of wet beneficiation processes greatly increased the use of water in minerals production. The growth in the mass mining and treating of huge quantities of low-grade rock made the availability of large areas of land for waste storage a necessity. The greater complexity and size of beneficiation and advanced processing plants also increased land requirements, and the more widespread use of large-scale surface mining techniques involved the disturbance of ever greater surface land areas. As the productivity of labor increased, the relative productivity of the land decreased.

D. CHANGES IN MINERAL PRODUCTION SINCE 1947

1. Changes in Mineral Output

Since the end of World War II, the productivity of labor in the minerals industry of the United States has climbed dramatically. At the same time, the productivity of the land (in terms of real value produced per acre devoted to mineral uses) has declined. The productivity of land that had been occupied in less productive uses, but which was converted to mining, however, increased. The effects on land and labor have been the result of many changes that have continued to take place in the mineral industries since 1947.

The output of most mineral commodities in the United States has increased substantially since the late 1940's. For some, such as uranium, the growth has been phenomenal. For most, it has been much less dramatic. For others, there have been declines as demand dropped or foreign sources of supply became dominant. Figures 43 through 56 demonstrate the changes that have taken place in the volume of domestic mineral output.

As the total outputs of different mineral commodities have changed since the end of World War II, so also have the tonnages of material mined in order to provide those commodities. The total volume of material handled in mining operations in the United States, as shown in Figure 57, has grown especially in the past decade, as changing technology as well as changing economic conditions have led to the greater utilization of lower-grade materials.

2. Changes in Mining Methods

Technology and economics have also influenced the changes that have taken place in the utilization of different mining methods. Ore production from underground mines in the United States more than doubled from 1947 to 1968. This substantial increase can be attributed to growth at a relatively few mines, since the number of producing mines decreased noticeably during this period.

All technologic trends in the mining industry (and trends in mining methods are only one example) reflect the industry's attempt to remain competitive by counteracting the ever-increasing unit costs of labor with greater productivity. Choices of mining methods and equipment made since World War II have, therefore, been overwhelmingly in favor of higher productivity, resulting in lower operating costs. In Table 31 are listed many of the main underground mining methods along with their average mining costs (in the period 1955-1959), and the labor content of these costs.

A very distinct trend away from the high cost, supported-stope methods toward the lower-cost open stope and caving methods has been evident since the 1940's. The room-and-pillar and stope-and-pillar methods have gained great popularity in the Western United States during this period, particularly in potash, trona, and uranium mining. Other lower-cost methods have also become important. Two enormous block caving mines, the Magma Copper Company's San Manuel mine in Arizona and the Climax Molybdenum Company's mine at Climax, Colorado, accounted for more than 40 percent of the nation's total underground ore production in 1966. Block caving is not a new mining method, however, as many of today's large open pit copper mines were block caving operations at some time in their history. In fact, during the 1947 to 1968 period, the relative importance of caving methods in the total of mine output actually declined because of the conversion of several block caving operations to open pit mines.

While some of the higher-cost mining methods (e.g., top-slicing and shrinkage stoping) are rarely used today, others (e.g., sublevel caving and cut-and-fill) have been revived by the application of new equipment and technology resulting in lower costs and higher productivity. The highest-cost underground mining method, square setting, has declined predictably in usage, but still is and will continue to be employed in weak but high-grade ore that cannot be mined profitably with any other method.

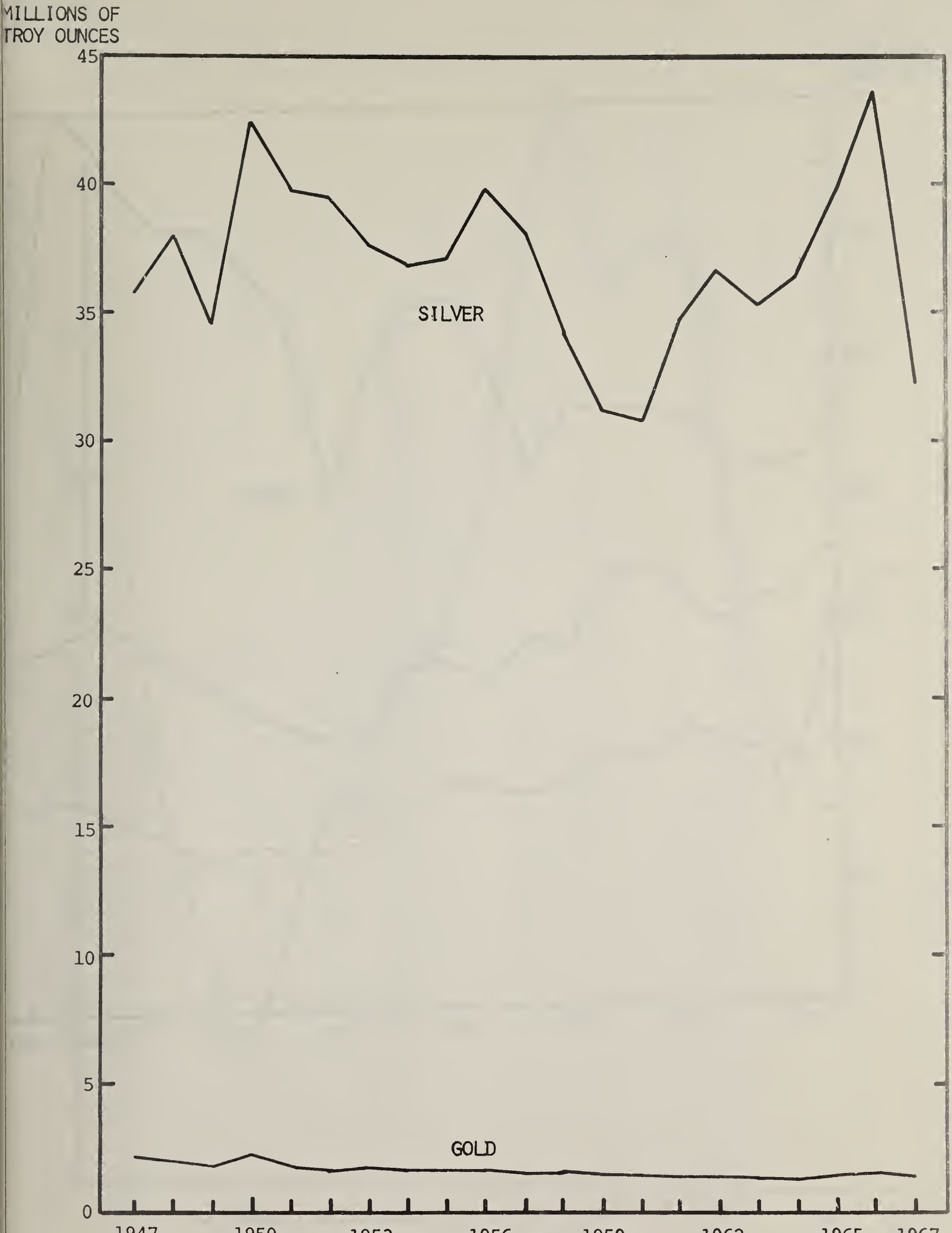


Fig. 43 - Precious metals production in the United States since 1947.

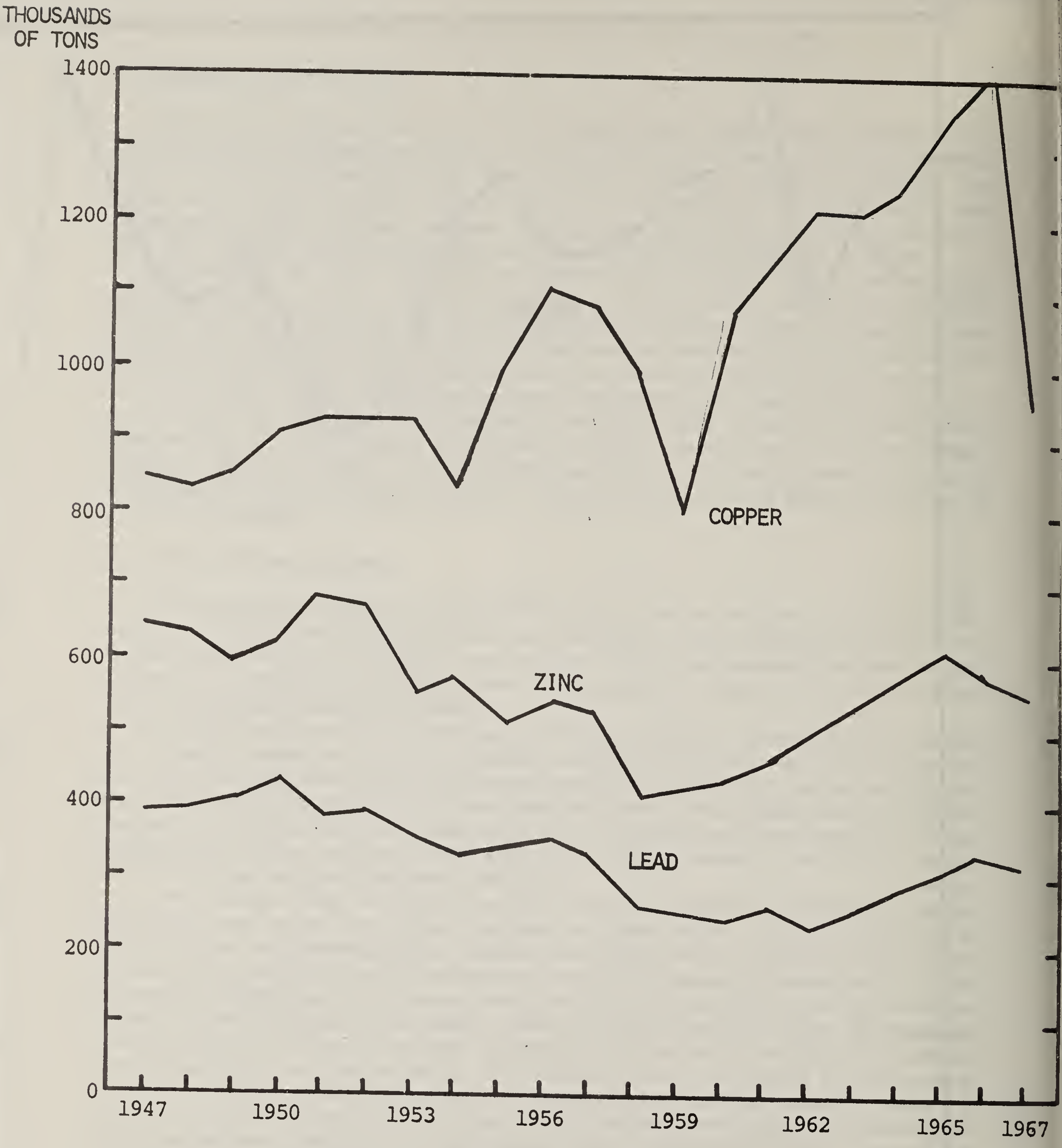


Fig. 44 - Nonferrous base metals production in the United States since 1947.

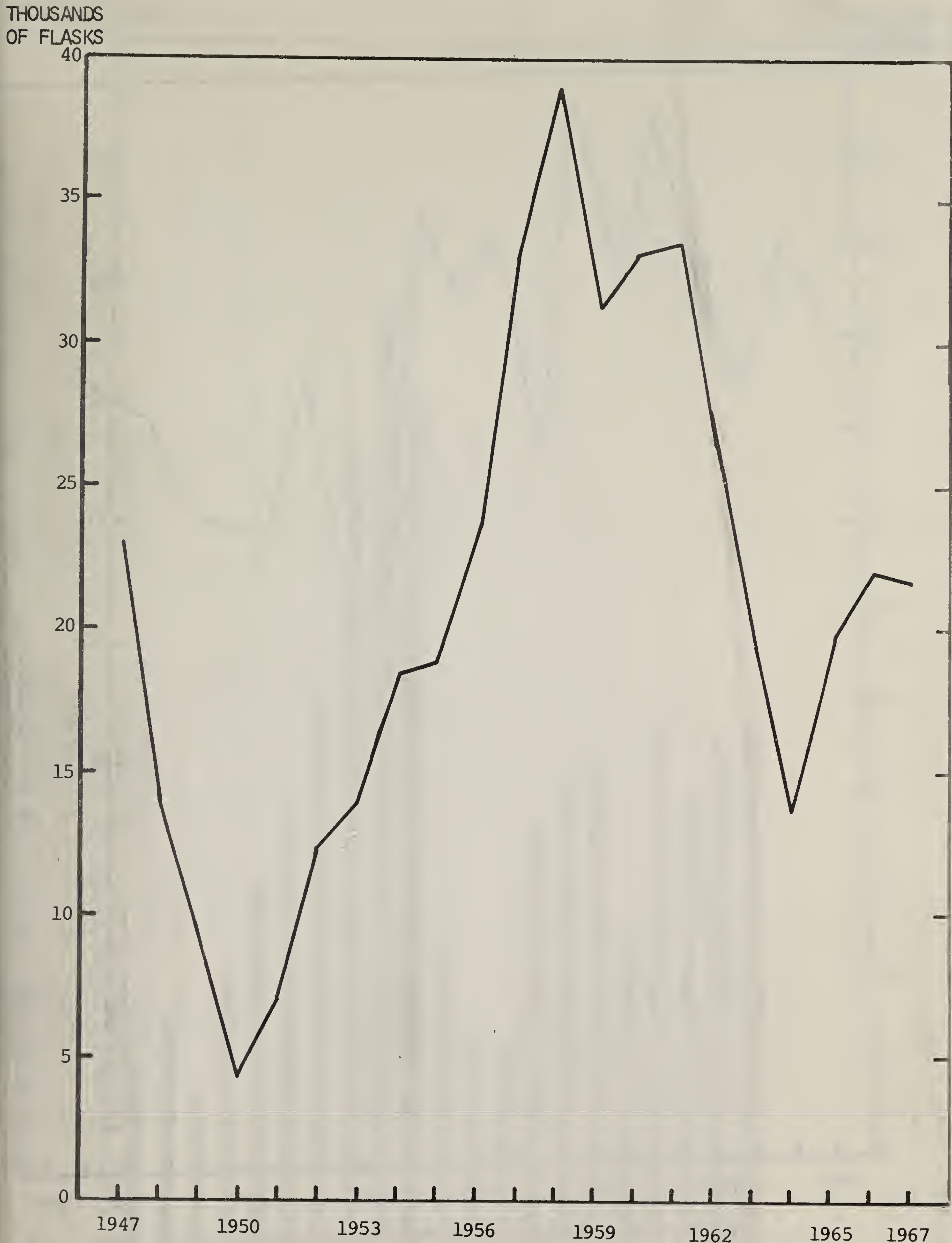


Fig. 45 - Mercury production from domestic sources since 1947.

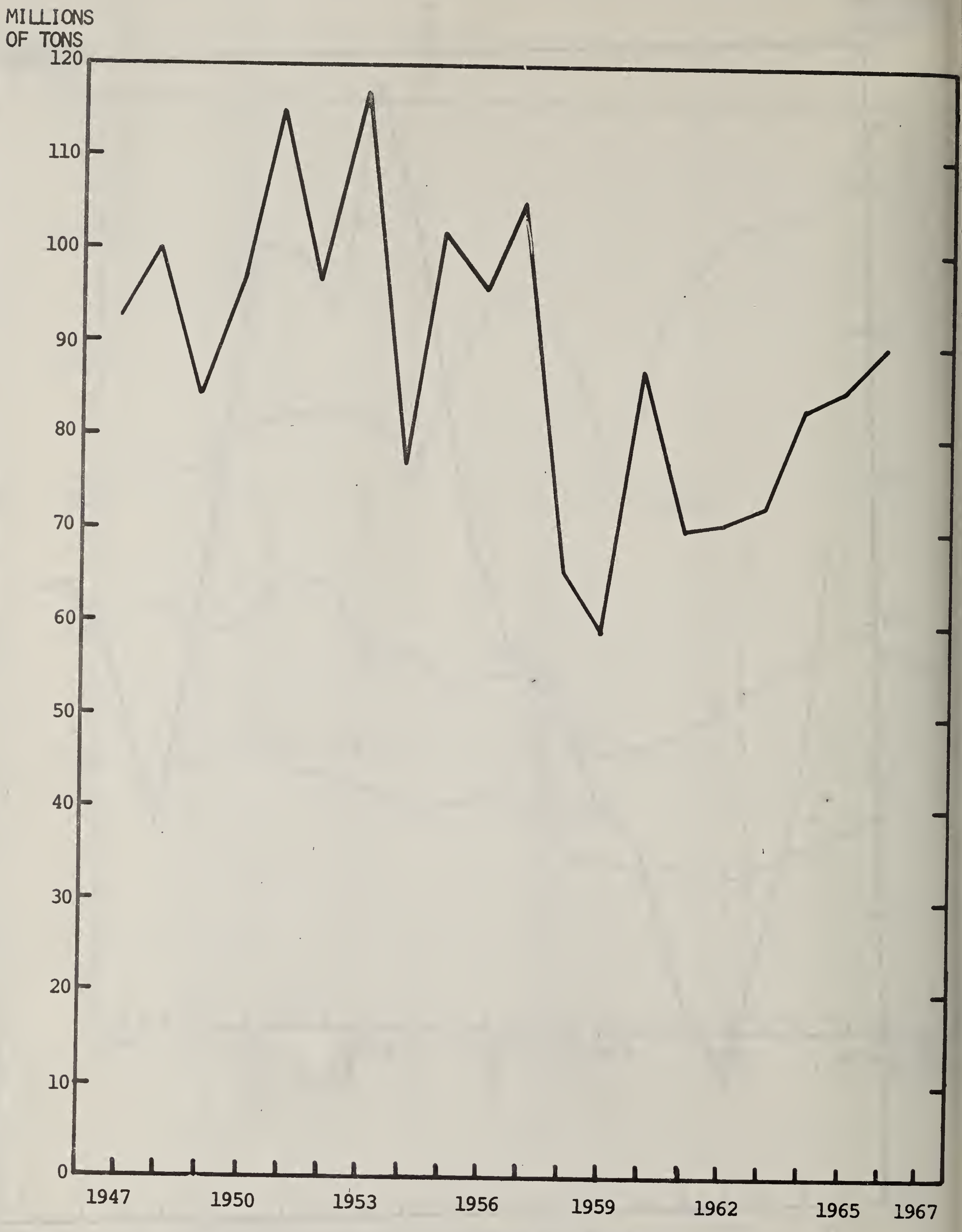


Fig. 46 - Iron ore production from mines in the United States since 1947.

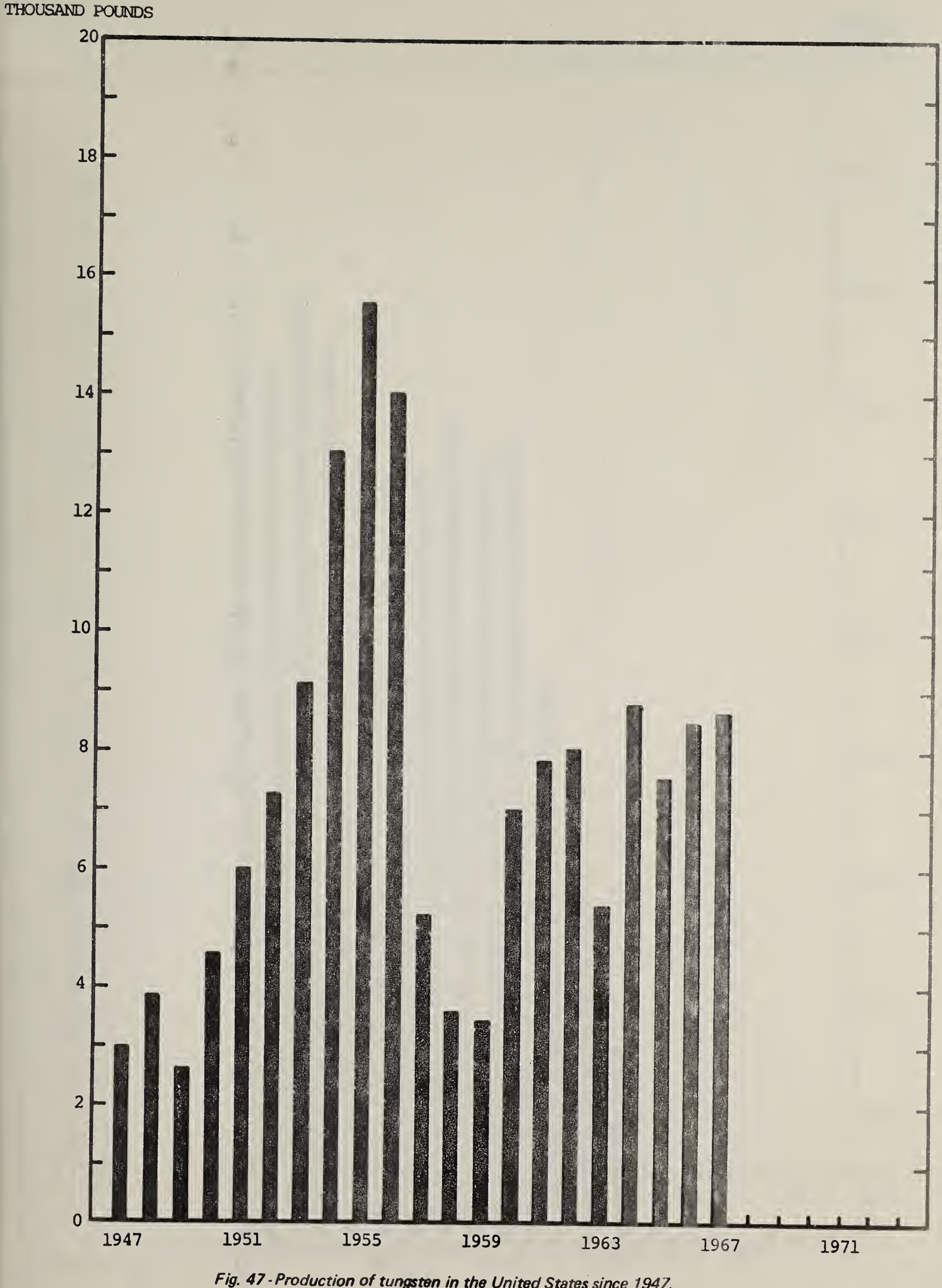


Fig. 47 - Production of tungsten in the United States since 1947.

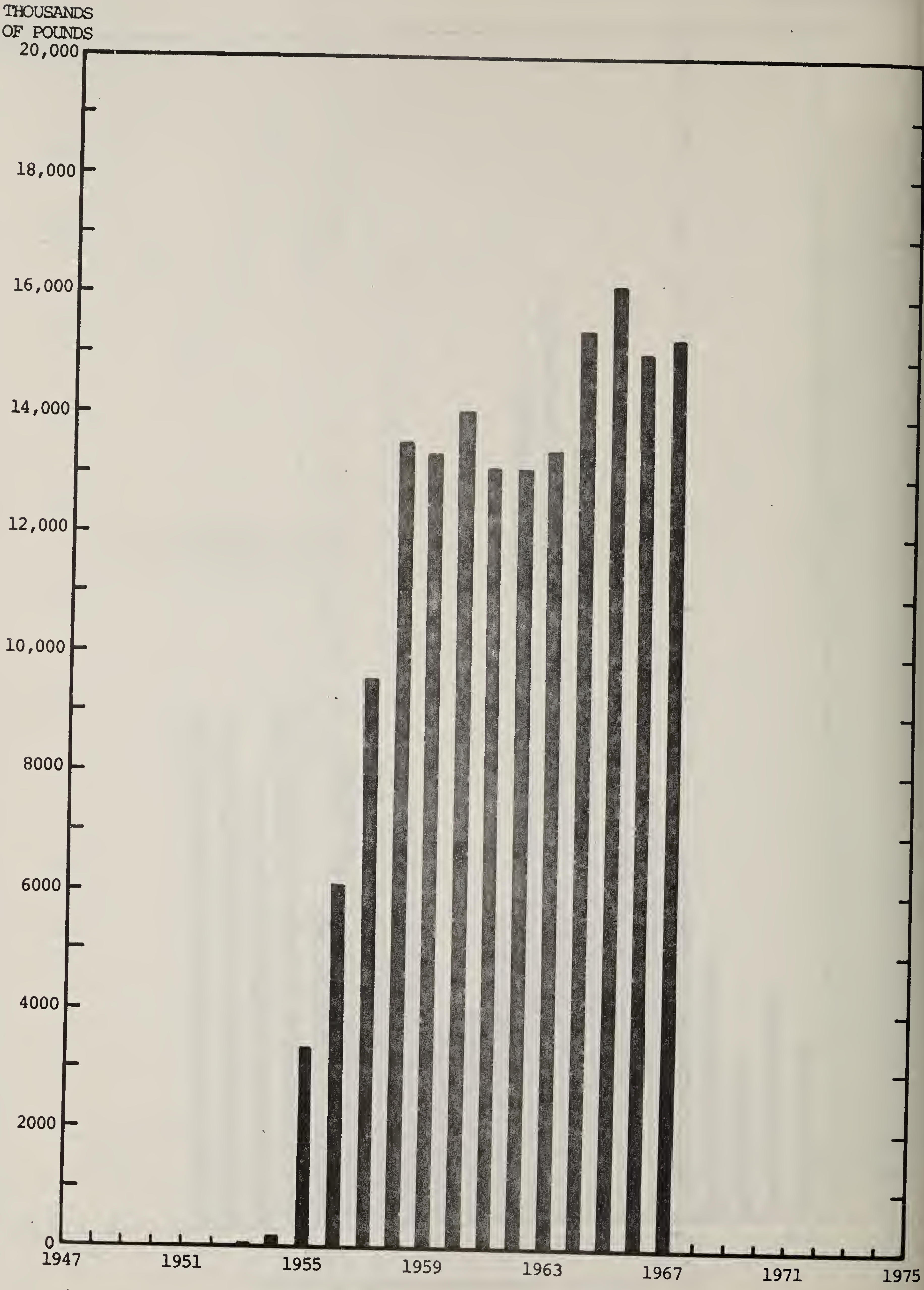


Fig. 48 - Production of nickel in the United States since 1947.

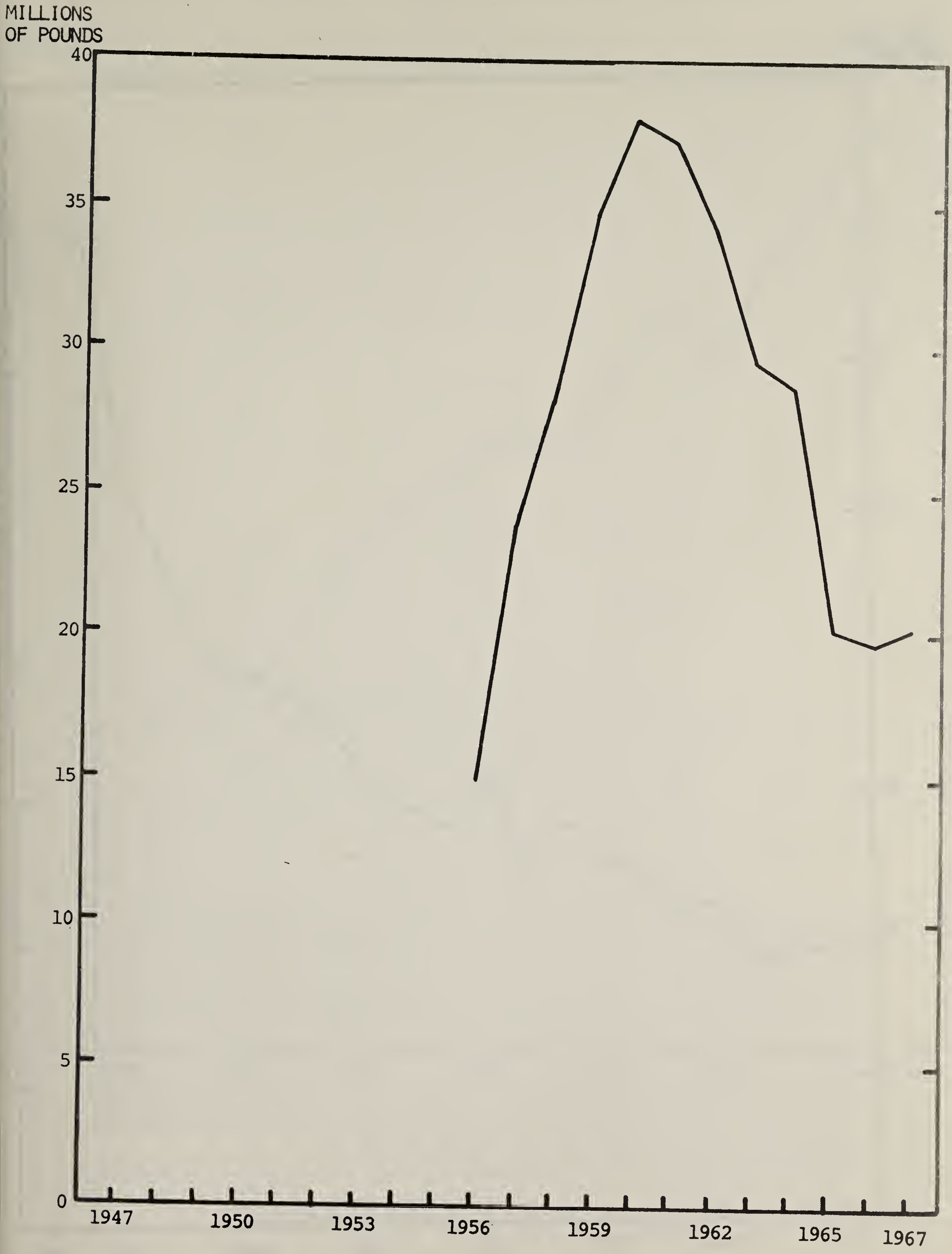


Fig. 49 - Uranium production in the United States since output data have been available in the 1950's.

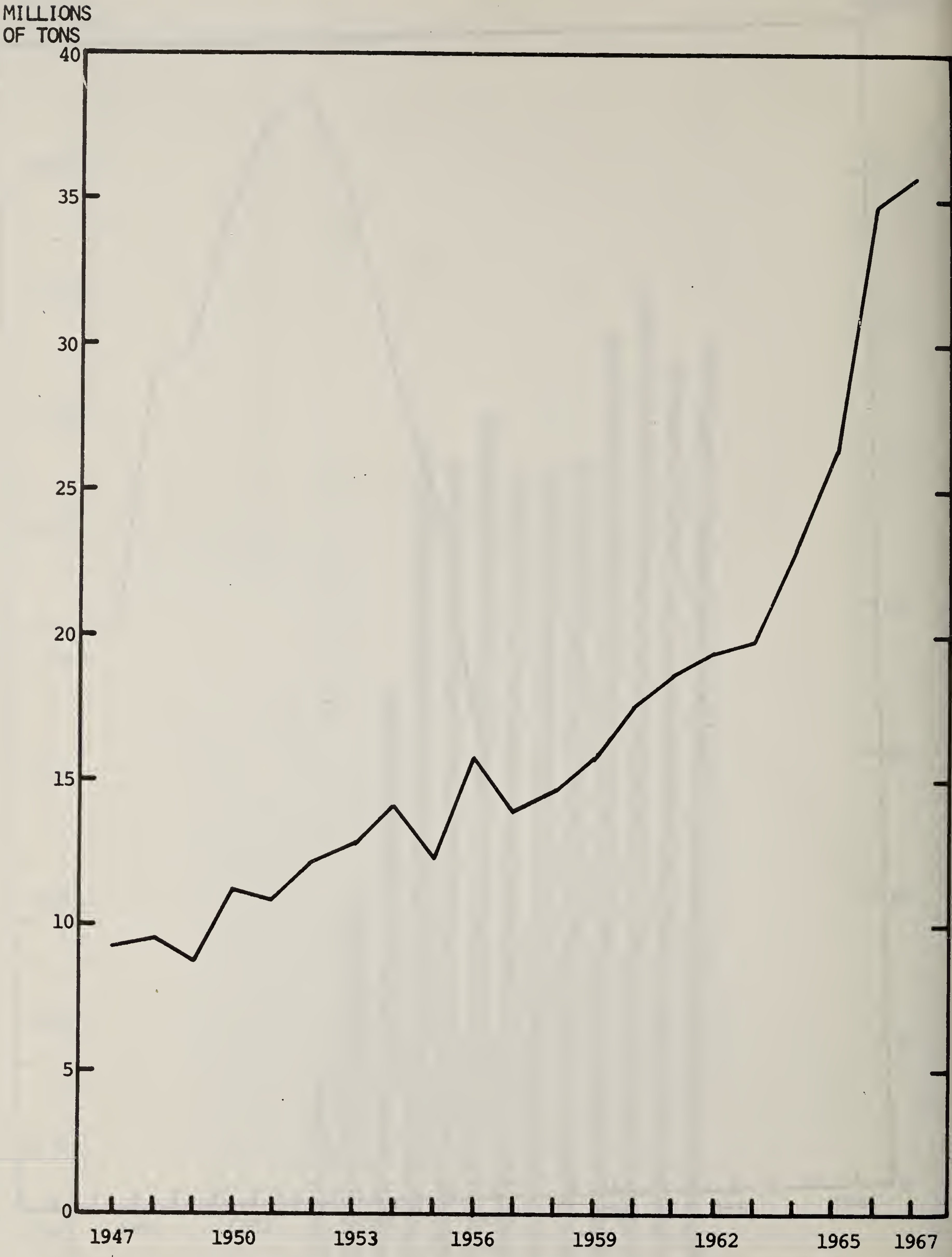


Fig. 50 - Phosphate production in the United States since 1947.

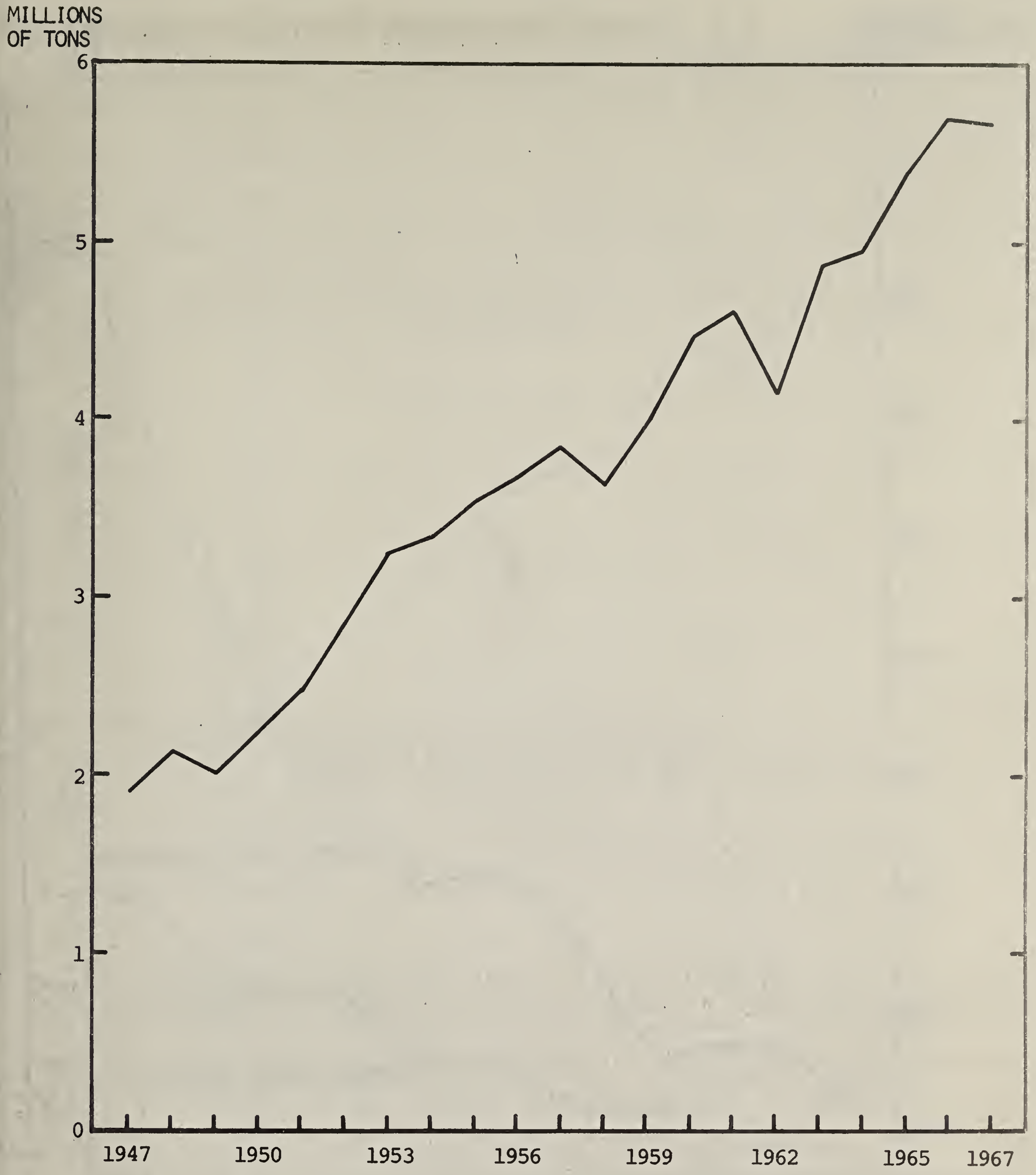


Fig. 51 - Potash production in the United States since 1947.

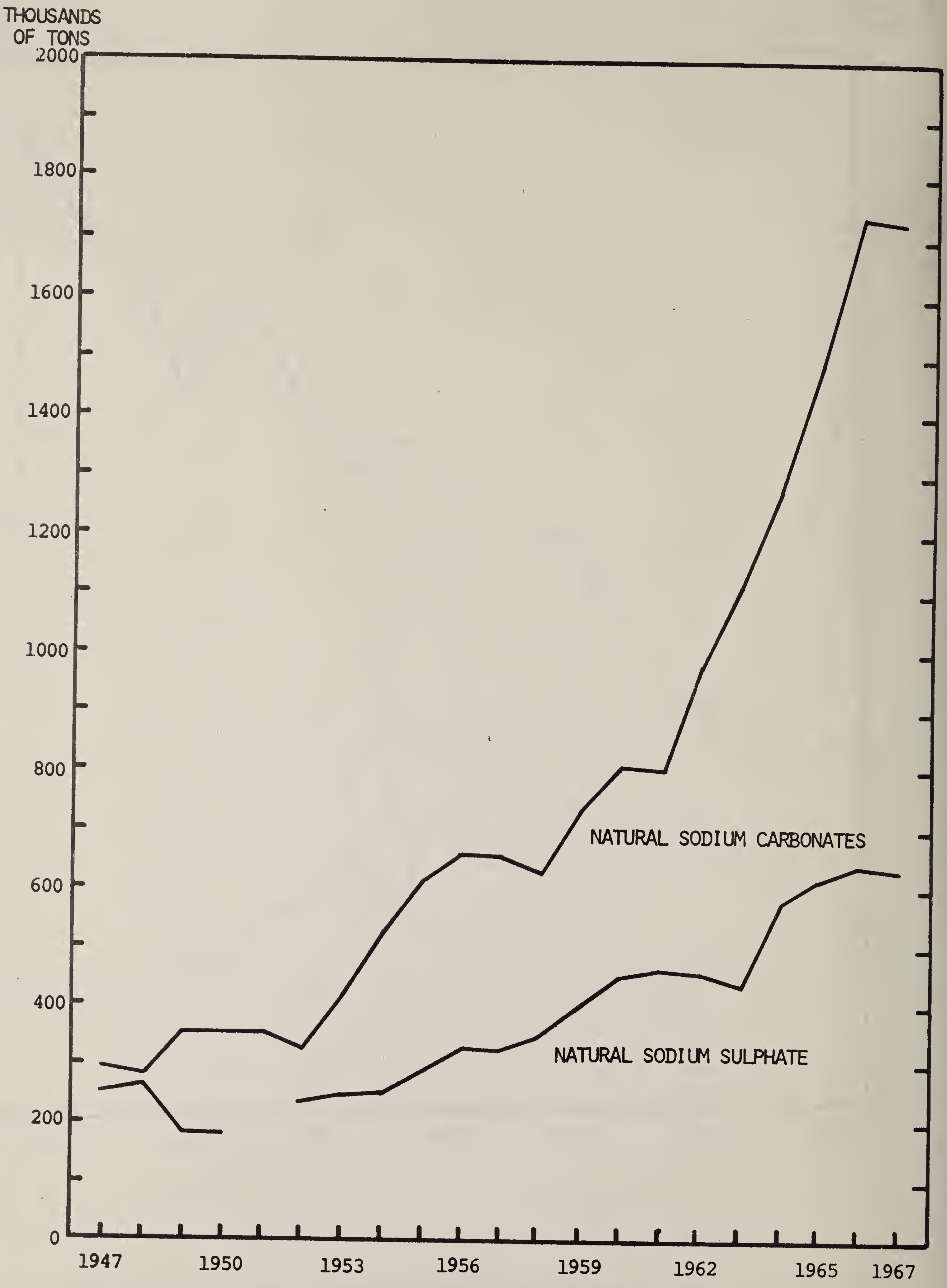


Fig. 52 - Mine output of soda ash and sodium sulfate in the United States since 1947.

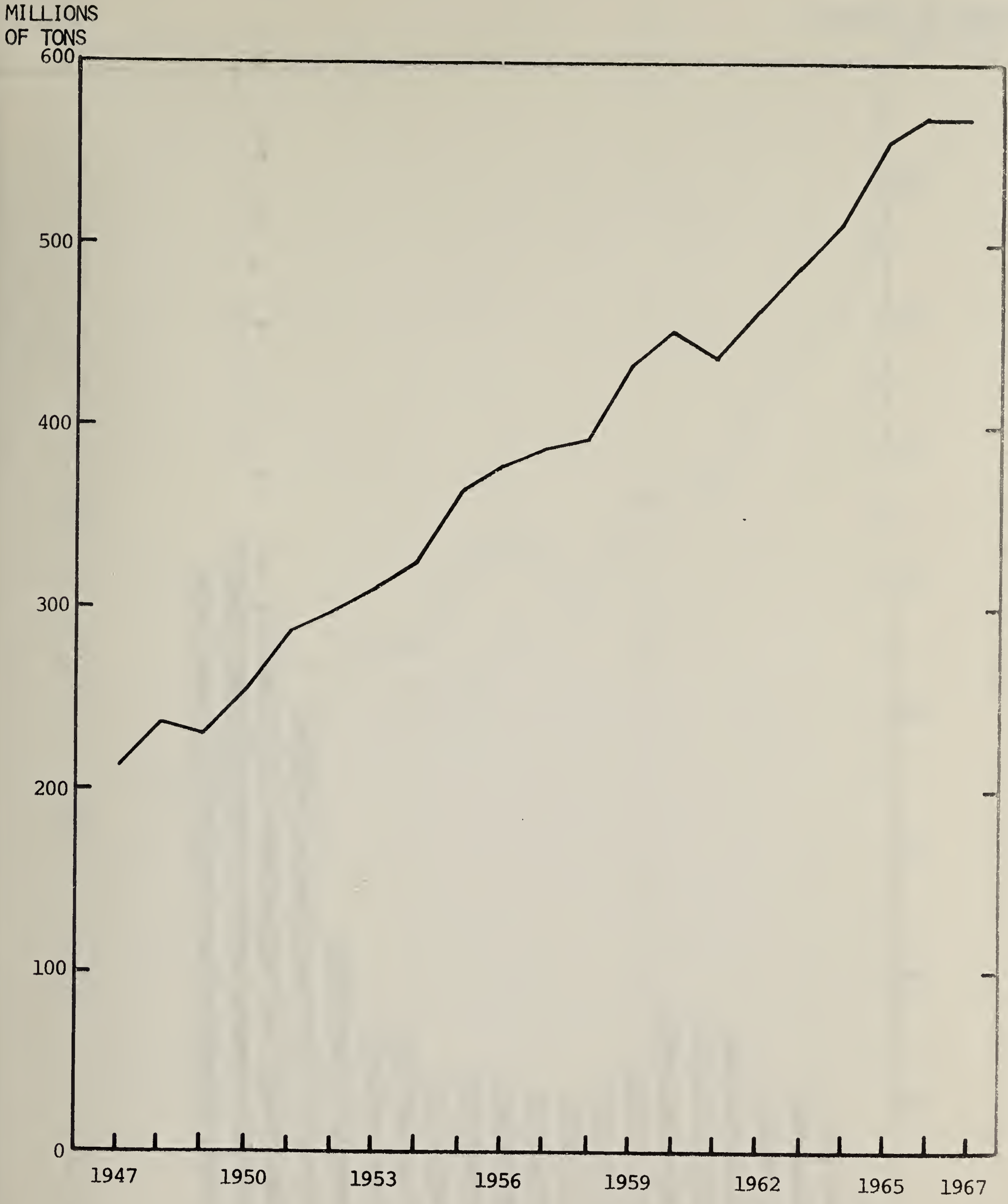


Fig. 53 - Limestone production in the United States since 1947.

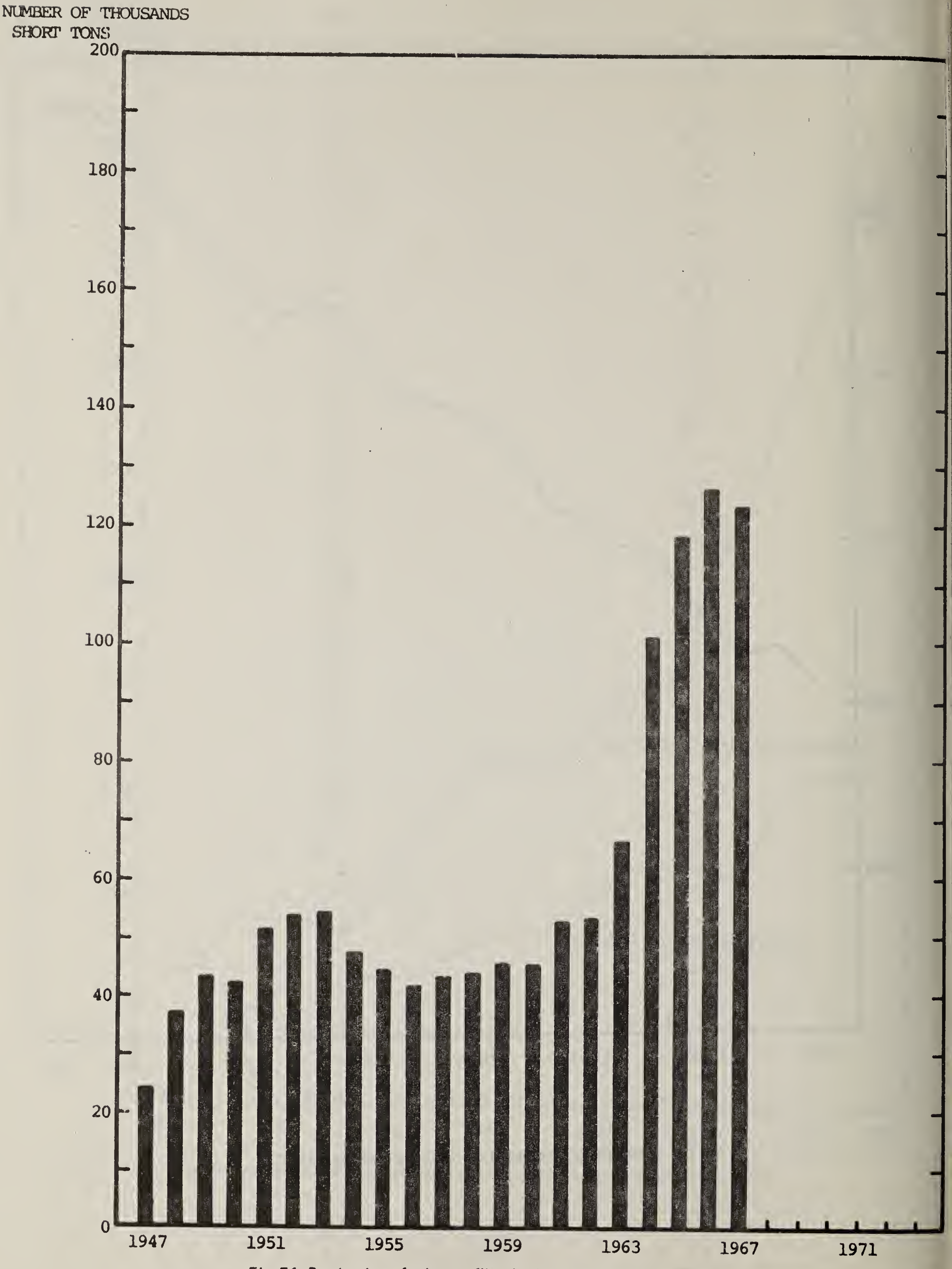


Fig. 54 - Production of asbestos fiber in the United States since 1947.

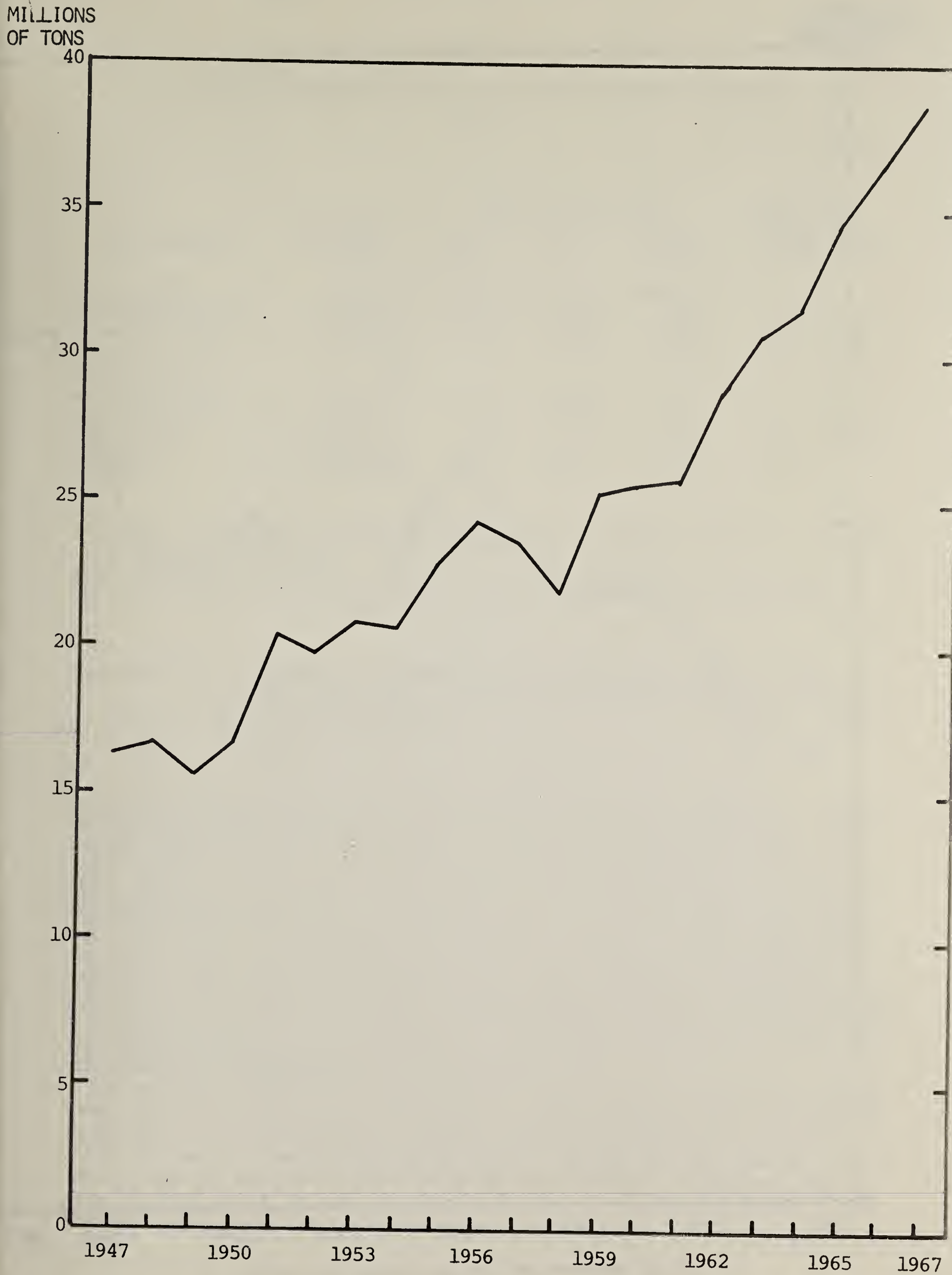


Fig. 55 - Output of sodium chloride salt in the United States since 1947.

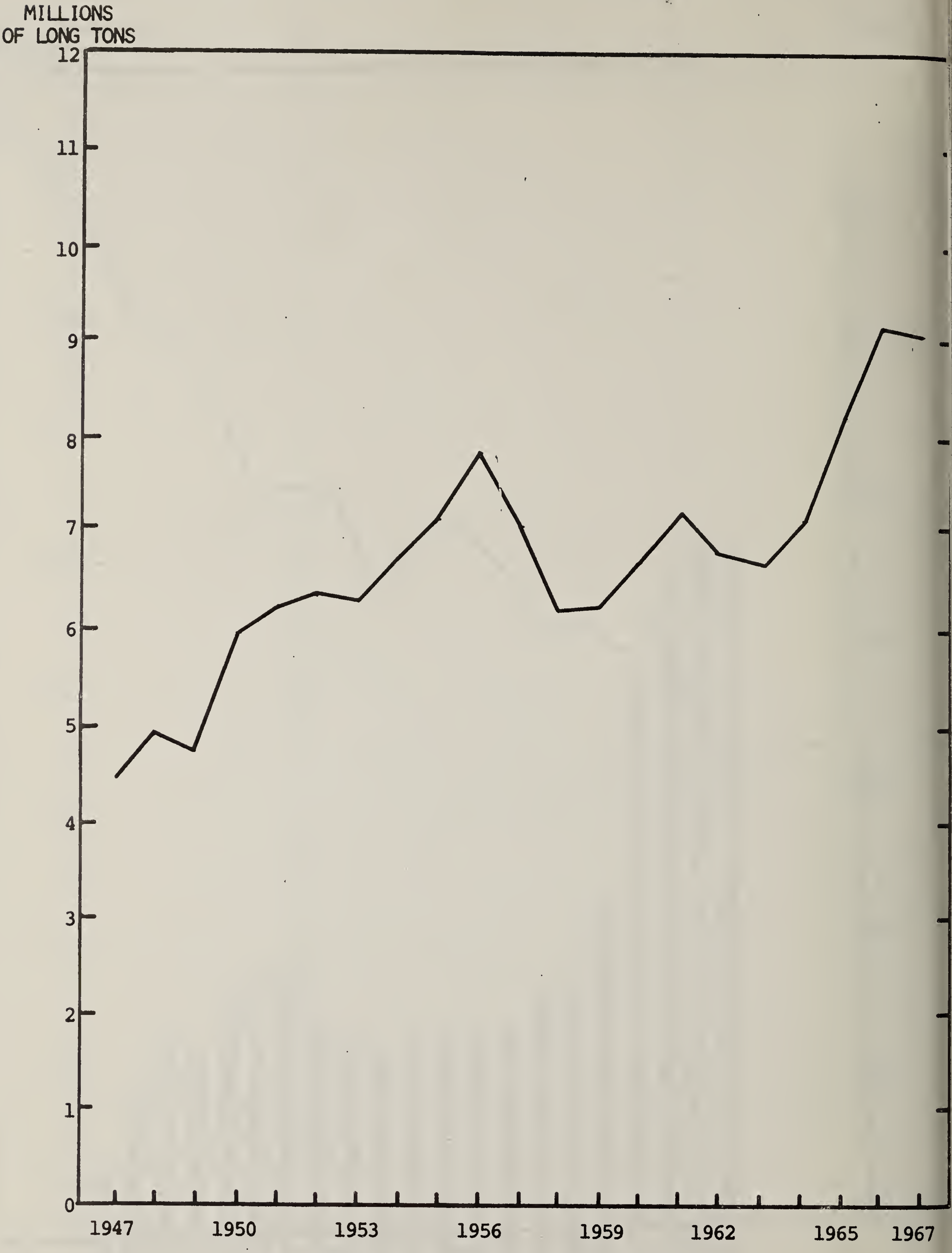


Fig. 56 - Sulfur production from domestic sources since 1947.

Table 31

DIRECT OPERATING COSTS FOR VARIOUS MINING METHODS 1955-59

Mining Method	Tons Mined Per Month	Direct Mining Cost/tons[a] High	Low	Average	Labor Cost (percent of total)
Square setting	439,330	$18.72	$6.22	$10.20	71
Cut-and-fill stoping	585,300	14.73	3.07	6.69	57
Shrinkage stoping	305,820	8.12	1.75	3.92	NA
Room-and-pillar (trackless type)	733,229	2.41	1.16	2.05	44
Sub-level stoping	1,547,410	4.71	1.06	2.37	57
Sub-level caving	118,150	NA	NA	4.97	63
Block caving	1,803,150	2.25	1.15	1.41	54
Open pit	5,198,060[b]	1.15	0.21	0.32	36

[a] Includes exploration and development, stoping, haulage, hoisting, pumping, and general underground and surface costs.

[b] Cost is per ton of "material" and is based on total tons of both ore and waste handled.

NA Not available.

Source of data: S. D. Woodruff, "Economic Valuation of Proposed Mining Ventures, Part II, Mine Development and Operating Costs," *Mining Congress Journal*, November, 1959, pp. 45-51.

In general, the trend in the use of underground mining methods since 1947 has been toward those methods that are best able to benefit from recent developments in cost cutting equipment and other technology, even though these methods may mean much greater capital investment. While the tonnage mined has increased for each of the three major categories of underground mining methods, only the natural support methods have increased their share of the total. In the past 20 years, the artificial support methods have lost favor as they usually have not been able to benefit from the newer, larger, higher-productivity mining equipment developed in recent years. The open stope methods have become much more popular because they can utilize more fully the newly developed equipment, and because many new mines have been opened in horizontal, stratified deposits where the room-and-pillar and stope-and-pillar methods are most economical. The growing importance of industrial minerals for the construction industry, agriculture, and as chemical raw materials has been a significant factor in the trend.

Block caving, virtually the only caving method used in western mines, competes most directly with open pit mining but has generally lost ground here in recent years. Surface mining does have a depth limitation, however, where the ore recovered can no longer pay for the vast amount of waste overburden that must be removed to uncover the ore. It is a distinct possibility that at some future date the economic pendulum will again swing back in favor of block caving, if some even cheaper method of underground mining is not developed. In-situ leaching or solution mining may be in that category.

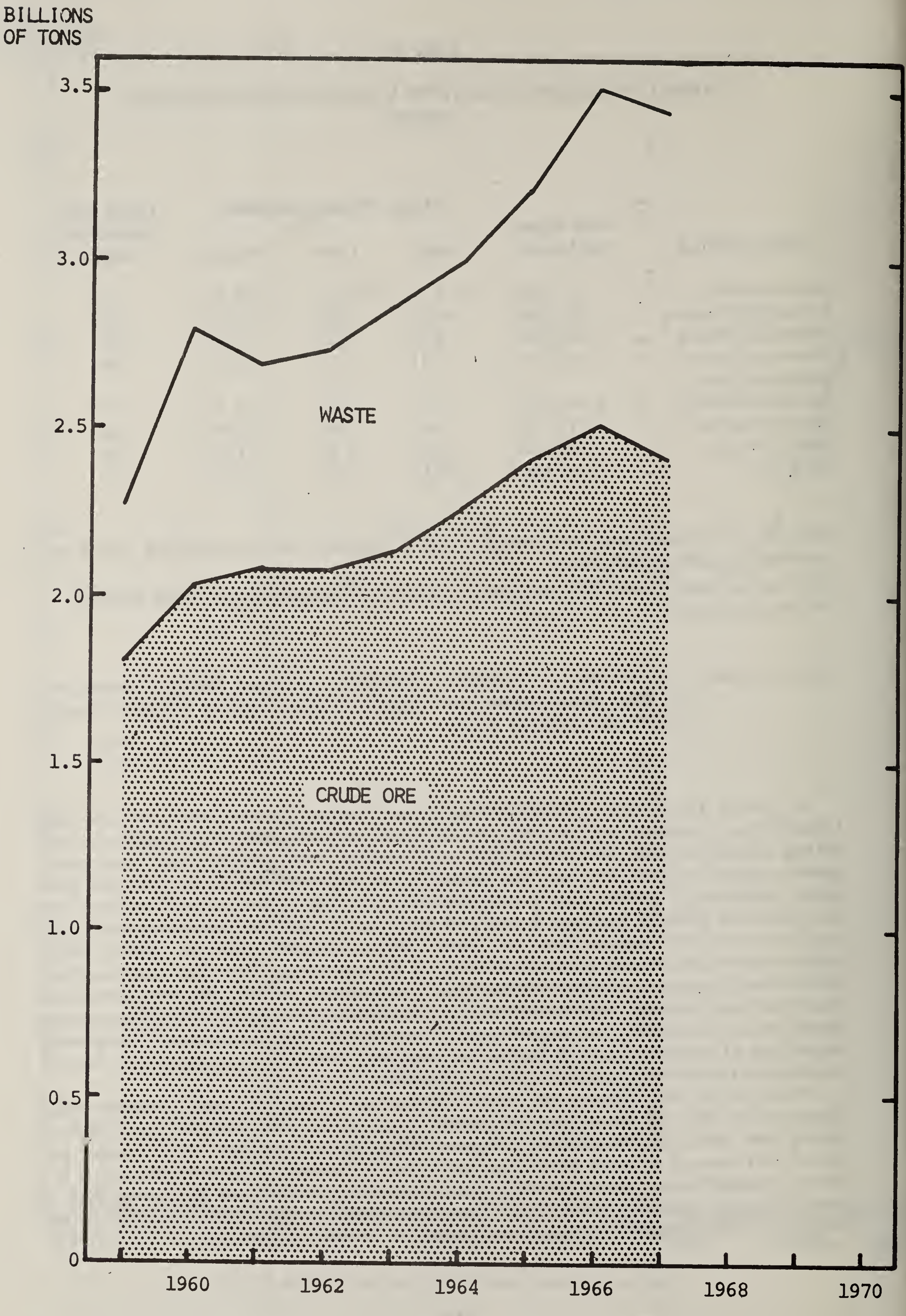


Fig. 57 - Total volume of material handled by both underground and surface mines in the United States.

3. Changes in Underground Operations

Equipment trends in underground mining since 1947 have been similar to surface mining equipment trends. In general, the objective of mining equipment developers has been to minimize the labor content of the various mining tasks. This has been achieved by building larger, faster, more mobile, more complex, and inevitably more expensive machinery. While the growth in size of surface mining equipment has indeed been startling, underground equipment has experienced a similar, but less visible growth.

The clearest trend in underground blast hole drilling has been toward the use of larger, heavier, and faster drilling machines, which in turn has required mobile mountings for the drills. The use of column-mounted drifters and stopers has declined significantly in the United States with the availability of higher output *jumbos* (vehicle-mounted machines). Following another trend in underground mining, the drill jumbos are now generally rubber-tired for greater mobility, and many are diesel-powered, again improving mobility.

No real breakthrough in percussion drills has occurred since 1947, but drilling speed has been increased mainly by using heavier, larger-bore machines. More powerful drills, larger feed motors, and rock bits with reconditionable tungsten carbide inserts have also made percussion drills economical for long hole work, formerly the domain of diamond drilling.

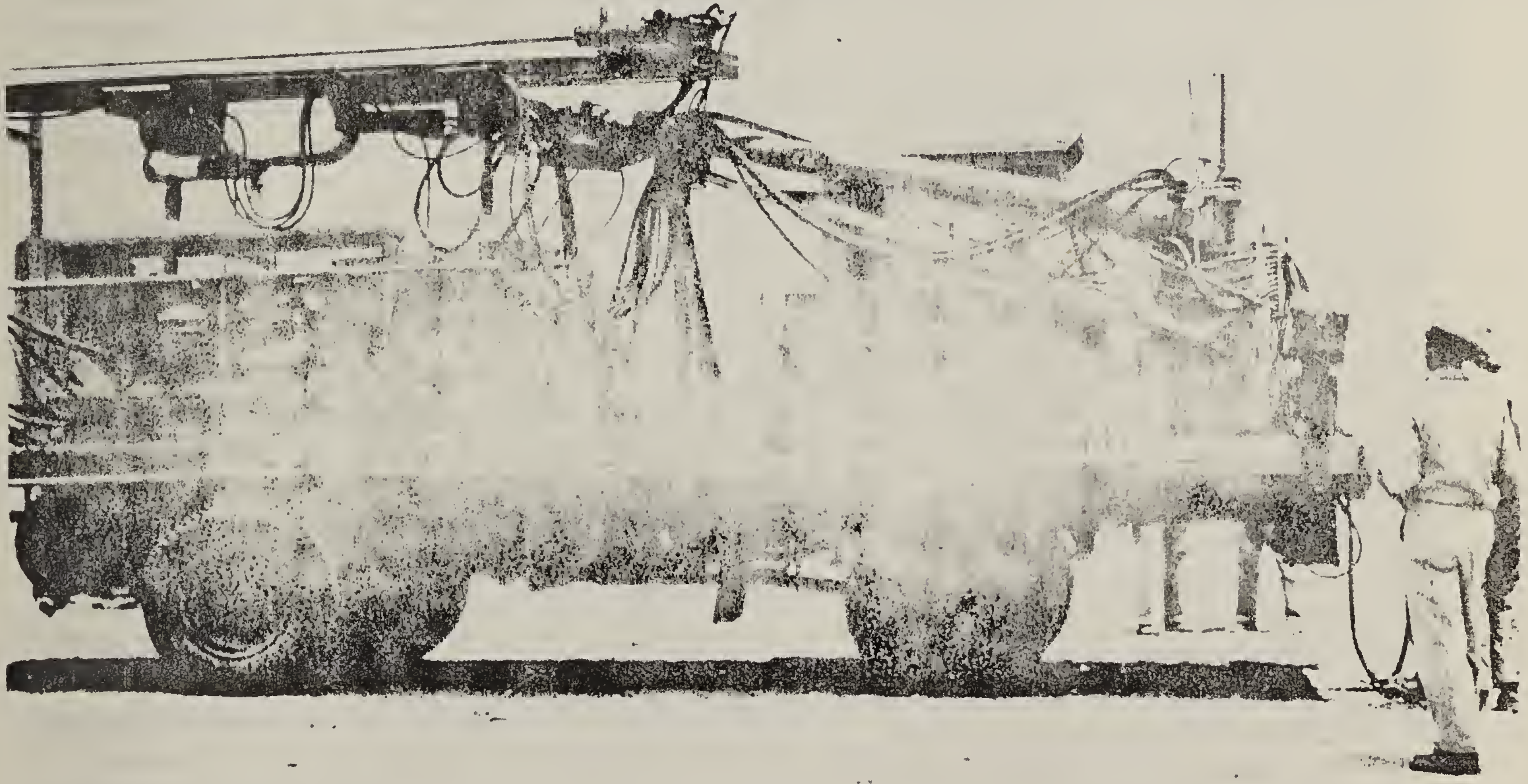


Fig. 58 - The development of larger, faster, more mobile, and more automatic drilling equipment has been a significant factor in the changes that have taken place in both underground and open pit mining since 1947. The above machine is used for secondary drilling in a large open pit operation.

Tungsten carbide-tipped percussion rock bits have probably been the most important innovation in underground mining equipment in recent years. Extremely hard, tungsten carbide has greatly increased bit life over the all-steel bits formerly used, thereby offering faster drilling speed, and greatly reducing lost time while bits are changed.

Although the trend has been less decisive in underground blasting than in surface mining, fertilizer-grade ammonium nitrate and fuel oil blasting agents have also become popular for underground use at the expense of the high explosive dynamites. The penetration of the underground mining market by the "fertilizer" blasting agents has been less complete than in surface mining, mainly because wet holes are more frequently encountered underground, and moisture destroys the sensitivity of most such materials. Other problems have also been encountered at particular mines.

Smoothwall blasting techniques have generated a great deal of interest in the past few years, and many mines employ one of these techniques to reduce overbreak in development openings. As a group, these techniques generally involve drilling closely-spaced holes which are subsequently loaded lightly with explosives. When detonated in the proper firing sequence, these holes produce a smooth wall, where the rock has failed between the closely-spaced holes, but overbreak, or excessive fracturing of the final wall and back, is minimized.

Loading underground in steeply dipping or massive ore deposits is normally a simple gravity process where ore is drawn from chutes into ore cars. Little can be done to reduce the cost of gravity, and as a result, only slight innovations have been made since 1947 in this operation. In horizontal, tabular deposits, however, a preference has been shown for rubber-tired, diesel-powered loading machines for maximum mobility. Usually only the size of the mine openings restricts the size of the loader used, and both have been growing larger in recent years. Conventional front-end loaders and even swing shovels have become common underground.

For in-stope haulage and for short distance primary haulage, the load-haul-dump machines have become very popular. These rubber-tired vehicles are operated by one man, are self-loaded, can haul at speeds up to 20 mph, and are self-dumping. They eliminate the need for separate operators for loading and hauling units. Nevertheless, rail haulage is still the most common method used in underground mining, although underground truck haulage has made some advances. Again, the flexibility and mobility offered by rubber-tired vehicles has proven advantageous.

As in the mobile equipment used in the other unit operations, diesel power has become increasingly popular for underground haulage units also, both in locomotives and in rubber-tired vehicles. Again, increased mobility has been the key factor.

In the "soft" rock mining of horizontal, tabular deposits, there has been a decided trend since World War II toward continuous mining and away from the conventional drill and blast operations. Continuous mining has become extensively employed in the enormous New Mexico potash and Wyoming trona deposits. The continuous breaking of hard rock has evolved much more recently with development of the big hole boring techniques. Shaft boring has been used successfully for driving vertical shafts to moderate depths in fairly homogenous rock. Oil field rotary-drilling methods are employed extensively, the major difference being the size of the bit used. Six-foot diameter shafts have been bored commercially to nearly 3,000 feet, and much greater diameters have been achieved in the federal government's underground nuclear testing program.

Raise boring has been used more extensively than the other boring techniques in metal and nonmetallic mining. Raise boring consists of drilling a relatively small (less than one foot in diameter) pilot hole, usually with conventional rotary methods, and reaming the hole to the desired size by working back in the opposite direction. Drill down and ream up is the usual cycle, but the opposite is used occasionally under unusual conditions.

Tunnel boring is performed with monstrous boring machines often called *moles*. These huge machines develop their own thrust and rotation, and load the broken rock into haulage conveyances at the rear of the machine. Moles have become capable of producing economical unit costs in all but the hardest or most complex formations. Boring machines suffer from a lack of flexibility when applied to mining, however, as the machines are very cumbersome, cannot negotiate sharp corners, and are very expensive. However, because of their excavating speed and high productivity, boring machines will probably continue to make inroads in underground mining development.

Other advances in the technology of mining have been made since World War II. Through geomechanics (the study of the response of rock to applied stress) the determination of inherent rock stresses and geologic structures has aided mine operators in several ways. Optimum pillar sizes and shapes have been determined, rock bolt patterns designed, and pillar failures and rock bursts predicted quite closely. Measurements have indicated areas of high stress in caving operations, thereby causing mining procedures to be changed. In other mines, knowledge of the existing stress field in the rock enables mine operators to orient mine workings to take best advantage of these stresses and greatly improve mine efficiency and safety.

4. Changes in Surface Mining Operations

There is a strong financial incentive for open pit mine operators to maximize the steepness of pit slopes. By doing so, costly waste stripping is minimized for the extraction of a given amount of ore. Applied geomechanics has aided in achieving this optimum by predicting maximum safe slope angles based on rock strength, inherent geologic structures, and ground water conditions.

Slope stability research has been successfully applied in two areas. First is the recognition that the optimum pit slope is not constant, but variable for different areas in any pit. This had improved upon the widely used empirical approach where all pit slopes were designed according to the characteristics of the weakest area of the pit. Second, the importance of slope monitoring has been demonstrated. Both displacement measurement and micro-seismic recording have been used to forecast slide activity in mines, thereby minimizing danger to personnel and disruption of mining activity. The work has also encouraged the optimum use of surface land area.

Since 1947, there have been a number of other significant economic and technologic trends in surface mining. These have resulted in increased production, a change in emphasis from underground to surface mining, and with few exceptions, an increase in the productivity of mining labor. Increased output has also been the result of a growing demand for more mineral commodities induced by an increase in population and higher per capita consumption. Mineral productivity has increased even in the face of the declining grade and quality of ores mined, which is indicative of the rapid technological improvement that has taken place in surface mining. These changes have permitted production from many formerly uneconomic mineral resources occurring near the surface at a time when the existence of higher-grade ores has become inadequate to meet increasing demand.

The general improvement in the productivity of surface mining since World War II can be attributed to several major innovations. Among the more significant have been the introduction of fertilizer-grade ammonium nitrate-fuel oil explosives, rotary drilling, a large truck haulage, and the greater capacities of both trucks and excavating equipment.

Immediately after World War II, the use of churn drills predominated in primary blasthole drilling in surface mining. Hammer drills, usually mounted on tripods or as wagon drills, were used for shallower secondary drilling. Churn drill holes, ranging from six to nine inches in diameter, were drilled from 30 to 90 feet in depth at a rate of 15 to 80 feet per shift, depending upon the hardness of the rock. Blastholes up to 12 inches in diameter were drilled for breaking overburden at some coal strip mines. Since then, other methods have largely replaced churn drilling. Where blasting is now required for breaking rock in surface mines, blastholes are drilled by mobile rotary, percussion, down-the-hole percussion drills, or jet piercing. Rotary drilling has become dominant in coal stripping and copper mining, while jet piercing has been adopted in iron mining. With rotary drills, holes are bored up to

15 inches in diameter at a rate about five times faster than that of churn drills, with a third to a fourth of the operating labor.

The fertilizer-grade ammonium nitrate blasting process was patented in March, 1955, by the Maumee Collieries Company, Terre Haute, Indiana. Since then, ammonium nitrate-fuel oil mixtures have virtually replaced all other blasting agents for surface mining. The first saving was in the price difference between dynamite and ammonium nitrate fertilizer. At present, the price of the fertilizer is less than a third that of dynamite. Metallized, ammonium nitrate slurries (which have been developed more recently) are more efficient in harder rocks and under wet conditions, and cost about two-thirds the price of dynamites.[123]

The full-revolving, crawler-mounted, electrically-powered shovel was in extensive use in surface mining prior to World War II, and is still the principal excavator used in open pit mining. In prewar years, power shovel dippers had reached a capacity of four to five cubic yards for excavating iron and copper ore and up to 33 cubic yards for coal stripping. The smaller shovels could load at a rate of 500 to 1,000 tons per shift with a two- or three-man crew.

Since 1947, in addition to larger power shovels, bigger draglines, scraper-loaders, and wheeled excavators have been developed for special conditions. Draglines now are used in stripping when overburden is relatively unconsolidated and where comparatively greater casting range is required. Wheel excavators, used extensively in Europe, have been introduced into the United States for excavating under conditions similar to those encountered in dragline excavation. The most significant change in power shovels has been the increase in size, bucket capacity, and dumping range. In metal mining, the number of shovels with a range of from 12 to 15 cubic yard bucket capacities has increased. In coal-stripping, shovel size and capacity have grown even more rapidly. Maximum bucket capacity for such machines increased from 60 to 70 cubic yards in the 1940's to 115 cubic yards by 1959. A shovel with a 180 cubic yard dipper capacity began stripping coal in Illinois in 1965. Still larger machines are planned. The bucket size of dragline excavators has reached 85 cubic yards.

Scraper loaders have become extensively used for stripping overburden where mineral deposits are small, the subsurface interface between waste and ore is irregular, and overburden is unconsolidated or soft. Much of the overburden over uranium and copper ores and phosphate rock is now stripped with these machines.

At the end of World War II, most haulage of ore and waste from large open pit copper and iron mines was by rail haulage, which even then was in a stage of transition from steam to electric locomotives. The acceptance of electrification was slow because of the problems involved in moving the necessary trolley wire electrical distribution system. The size of steam locomotives then in use at open pit copper mines ranged from 55 to 90 tons and size of electric locomotives was about 75 tons. Ore cars had capacities of 90 to 100 tons. About a dozen open pit iron mines were wholly or partially electrified, with locomotives ranging in size from ten to 75 tons.

Since 1947, most material from surface mining has been hauled by rail with electric or diesel-electric locomotives. Although a minor amount of material was moved by trucks even before that time, it was not until the mid-1950's that the trend to truck haulage was accelerated. Virtually all surface mines opened within the last decade have adopted truck haulage, and less than a dozen older mines continue to use rail haulage from pits for some part of their transportation system, and then only where haul distances are longer than a few miles.

As the use of trucks has grown, so also has the size of those trucks. From the 35-ton vehicles common in the early 1950's, the capacity of the average open pit haulage truck has grown to nearly 100 tons, and even 200-ton capacity trucks are now in use at some operations. A haulage unit of 240 tons capacity is being used for surface coal mining in Illinois.

Other means of open pit ore and waste haulage have also been developed over the past 20 years, and some have seen extensive use in both underground and surface mines. The

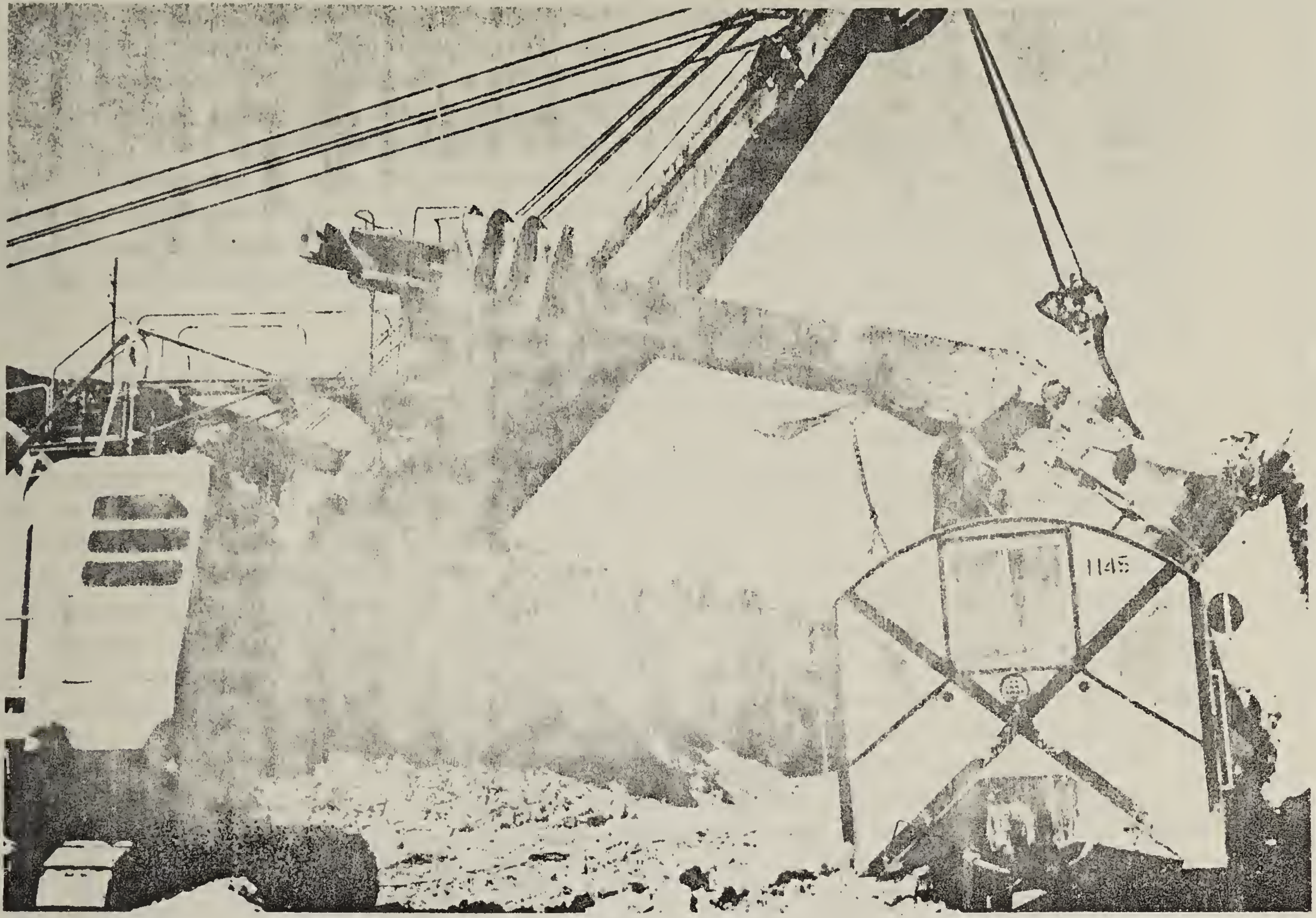


Fig. 59 - Since 1947, there has been a strong trend toward the use of larger equipment in materials handling in both underground and surface mines. The introduction of very large trucks has all but eliminated the use of railroad haulage in surface mining, except in the very large open pit operations such as in this one at Morenci, Arizona.

conveyor belt is one of these that has gone from common usage in beneficiating plants to use in mining operations as well. By far the greatest use has been in underground haulage in conjunction with room-and-pillar methods in horizontal bedded deposits. In open pit operations, belt conveyors have been and are being installed primarily to convey stripped waste material to dumps.

A chiefly underground device has also been adapted to open pit mining within the last two decades. Inclined skip hoisting has been attempted at a few smaller, deep, relatively compact open pit mines, but its use has been limited.

5. Commodities and Changing Mining Methods

The numerous changes that have taken place in mining technology since 1947 have not been uniformly applicable in the production of all commodities. Nevertheless, the use of surface mining methods has become more and more prevalent in most segments of the mining industry of the United States. Although there have been some differences according to commodities, these differences (except in a few cases) are slight.

The proportion of gold ore mined in the United States by surface methods climbed gradually from about 20 percent in 1947 to a high of about 28 percent during the three year period from 1961 to 1963, then dropped to 24 percent in 1964. With the development of new deposits in North-Central Nevada, however, the surface mining of gold became much more important, and in 1965 the percentage of gold ore produced from mines using surface methods climbed to 40 percent of total domestic output. Previous to the development of the deposit at Carlin, Nevada, most of the gold produced in the United States by surface mining methods had been produced as a by-product in the mining of copper and other base metal ores. The increase in 1965 was attributable primarily to the new mines in Nevada which produce gold from disseminated deposits at or near the surface and which are mined specifically for their gold content. In 1966 the percentage of gold produced from surface mining methods in the United States climbed to 44 percent. In 1967 there was a slight decline, but the trend appeared to be continuing upward.

Since 1947, there has not been such a dramatic shift in the mining of base metals from surface deposits as has occurred in gold mining. From 1947 to 1952, the percentage of copper mined by surface methods in the United States climbed steadily from about 73 percent in 1947 to approximately 85 percent in 1952. Thereafter, new developments in large-scale underground mining caused the percentage of copper ore produced from surface mines to decline to about 76 percent in 1958. Two mines, the White Pine copper project in Michigan and the San Manuel Mine in Arizona, both using large-scale but distinct underground mining methods (block caving at San Manuel, room-and-pillar at White Pine), accounted for most of this decrease in the relative importance of surface mining methods. Since 1958, however, the importance of surface mining methods in copper production in the United States has risen. In 1967, more than 85 percent of the copper mined in the United States came from surface operations.

The amount of silver mined in the United States by surface methods has climbed rather steadily since 1947, except for a rather sharp increase in 1960. This was due in large part to major expansions at surface mines which produce silver as a by-product, however. In 1947, approximately 11 percent of the silver mined in the United States was mined by surface mining methods. This climbed only gradually until 1959, when a sharp increase sent the total up to 17 percent of total domestic production. Since that time, the total has declined to 15 percent (in 1963), climbed again to a high of 19 percent (in both 1965 and 1966), and then dropped again to 16 percent (in 1967). Although there have been such sporadic ups and downs in recent years in the percent of silver ore mined by surface mining methods, the trend followed has been rather persistently upward.

The percent of iron ore produced in the United States by surface mining methods, already high at the close of World War II, has climbed consistently since then. In 1947, approximately 75 percent of the iron ore produced in the United States was mined by surface methods. This proportion rose steadily to 1963, when a high of 94 percent was reached. The same percentage was achieved in the following year, but since then has fallen off to a little more than 90 percent. With nine out of every ten tons of iron ore produced in the United States already coming from surface mines, it may be that a temporary ceiling in the importance of surface mines may have been reached.

Uranium mining in the United Staes has seen a pattern for surface mining methods somewhat different from those of the other nonfuel minerals. In 1948 and 1949, very little of the uranium ore produced in the United States was mined by surface methods. In fact, between 98 and 99 percent came from underground mines.

In 1950, however, the importance of surface mining methods began to increase. In that year, a little more than one out of every ten tons of uranium ore mined domestically came from surface mining operations. This ratio climbed steadily to about one in four tons in 1954, then dropped somewhat to less than one in five tons in 1955. In the late 1950's, however, the proportion of the nation's uranium ore mined by surface methods rose rather sharply to almost 40 percent until 1958, when the share accounted for by open pit mines again dropped to about 25 percent. Over the past ten years the percentage of uranium ore mined by surface methods has increased gradually along a rising trend to about 30 percent.

Even in the past two decades, when the growth of open pit mining has been substantial among most nonfuel minerals, the mining of mercury has remained essentially an

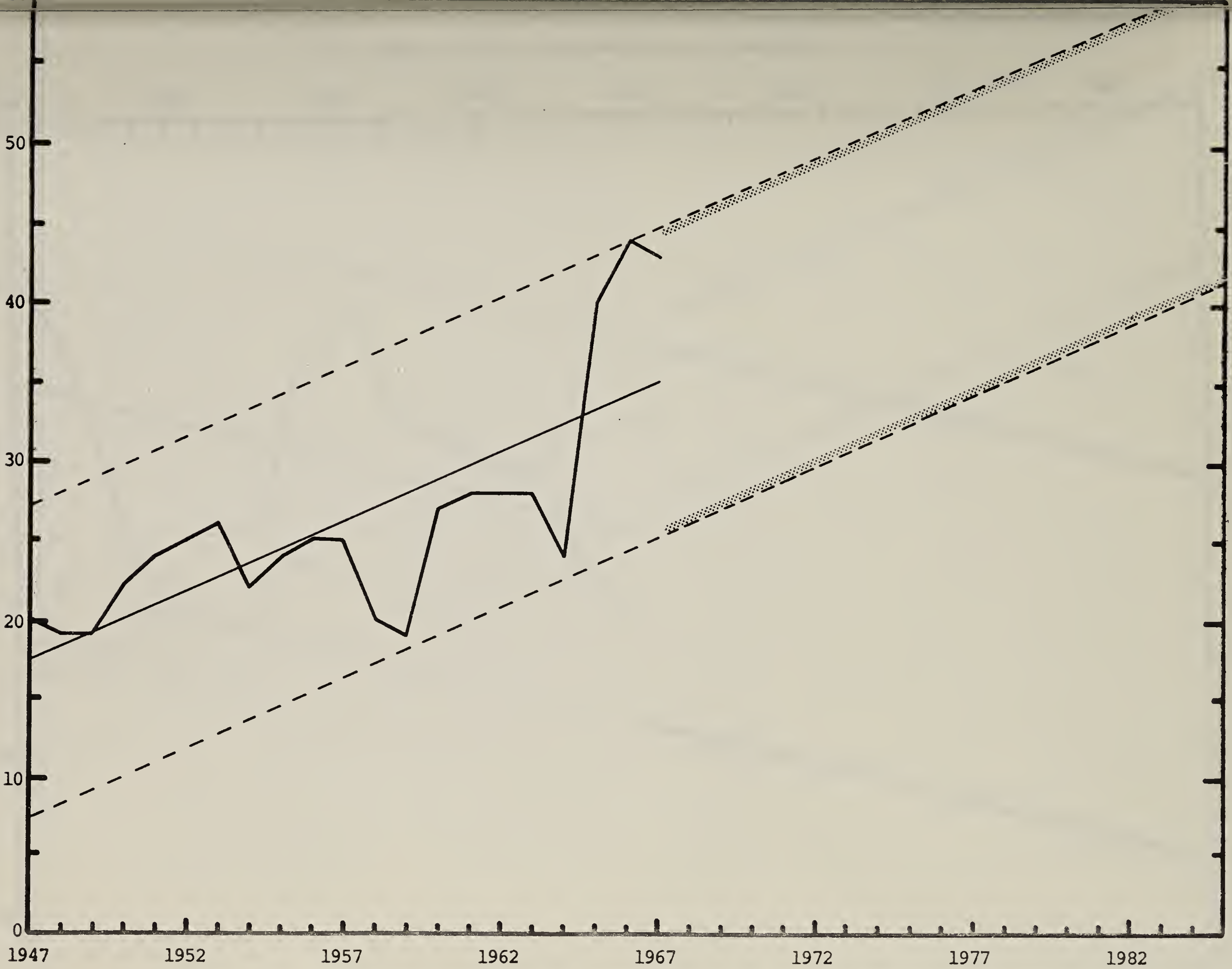


Fig. 60 - Gold ore mined by surface methods in the United States.

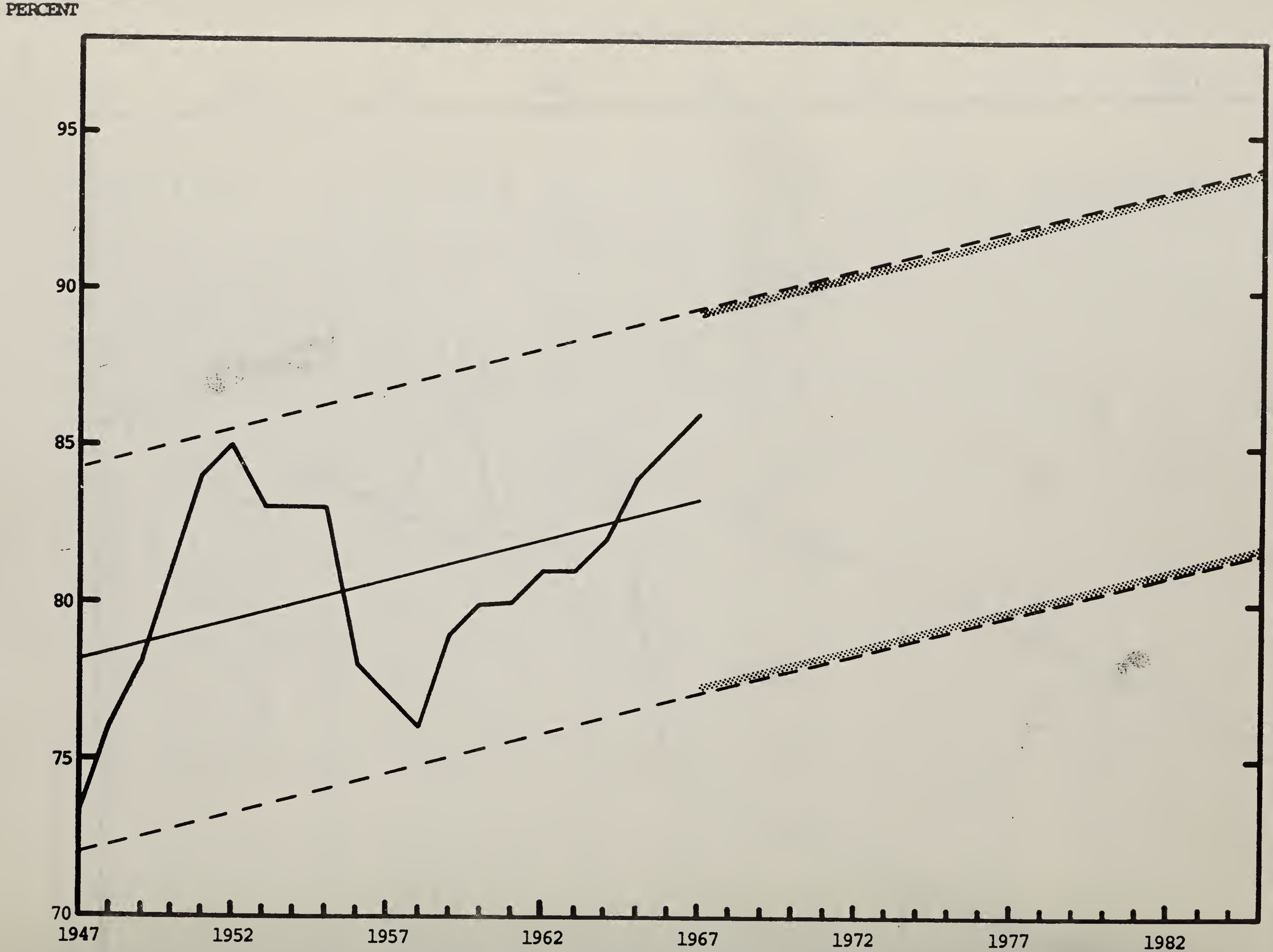


Fig. 61 - Copper ore mined by surface methods in the United States.

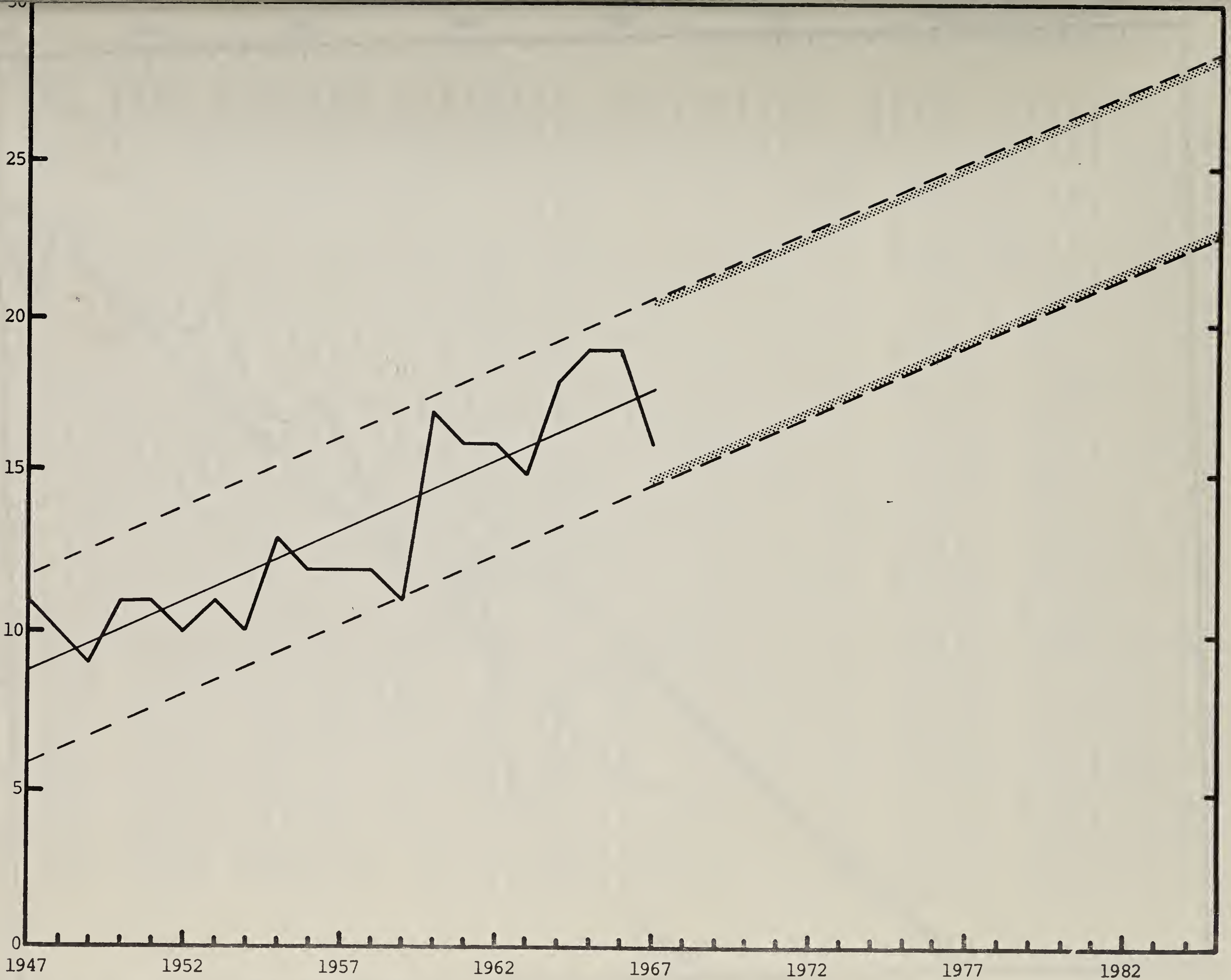


Fig. 62 - Silver ore mined by surface methods in the United States.

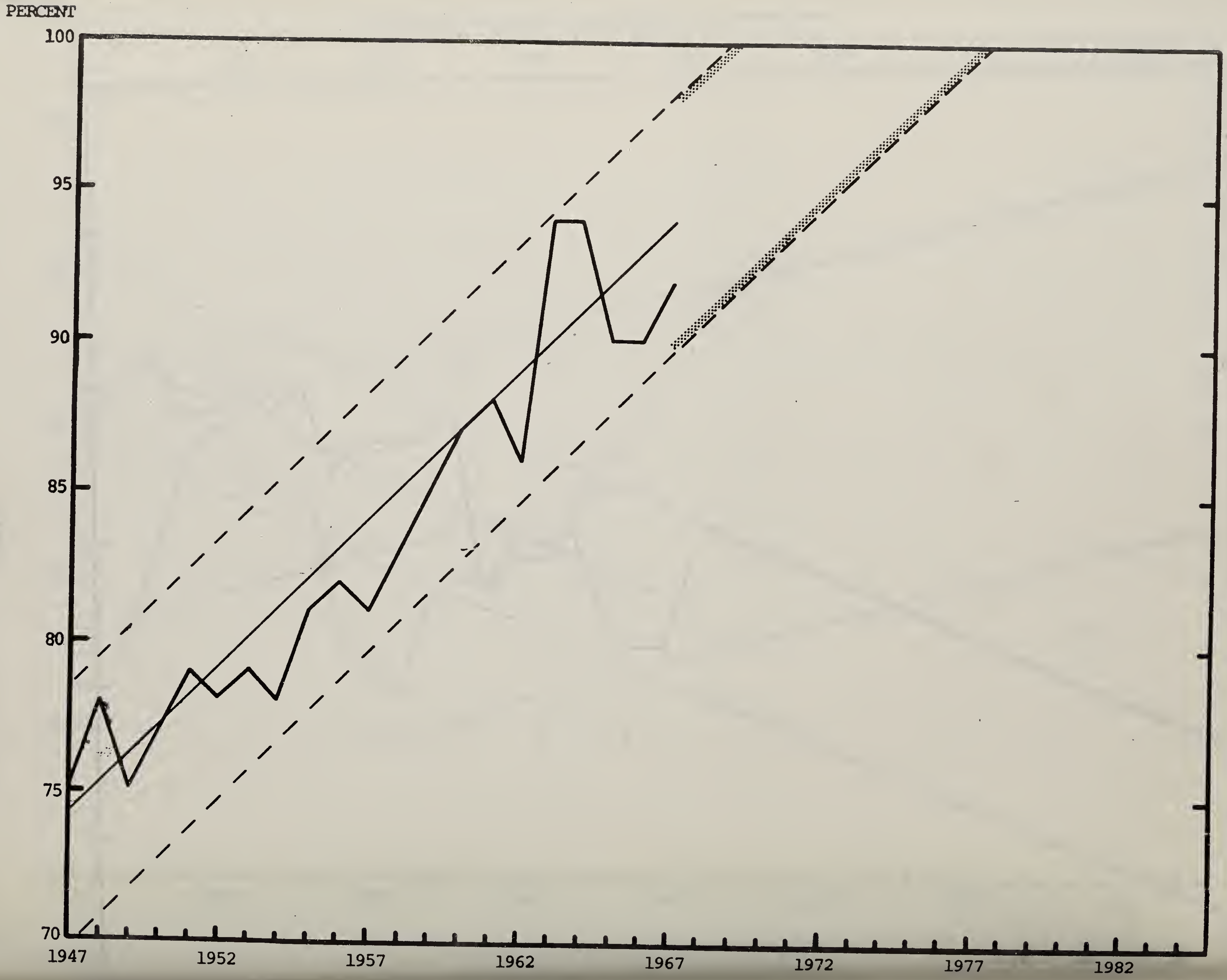


Fig. 63. Iron ore mined by

underground venture. Since 1947, the percent of mercury ore mined in the United States by surface methods has undergone a rather erratic pattern but has remained relatively small.

In 1947, approximately nine percent of the nation's total mercury production came from surface mines. This increased shortly thereafter to 11 percent, then dropped to zero in both 1949 and 1950. With the advent of the Korean War, the percentage of mercury produced from surface mines again began to increase, rising to a high of seven percent, but dropping again to only three percent in 1956. In 1957, however, new developments in the industry sent the percentage of surface mined mercury ore up sharply (to 20 percent), followed by a rise in 1958 to 26 percent. Since then, there has been a rather erratic decline to 20 percent in 1967.

Unlike mercury, at the present time (and over the past 20 years) virtually all of the phosphate rock mined in the United States is mined by surface methods. In 1947, 98 percent of the nation's phosphate rock was produced from surface mines. This proportion held constant until 1961, when it rose to 99 percent. Since that time, the share of phosphate production accounted for by surface methods has held relatively steady at 99 percent.

The proportion of potash mined in the United States by surface methods has been just the complement of the phosphate rock share. In 1947, approximately 84 percent of the potash mined in the United States came from underground mines rather than surface operations. This dropped slightly to 83 percent in 1949, and this has been the low figure for the entire 20 year period since World War II. During the Korean War and subsequently, the percentage of potash coming from underground operations climbed, reaching a high of about 92 percent in 1955. The proportion coming from underground mines then remained rather steady, climbing to almost 93 percent in 1961 and then dropping to 90 percent in 1962. Since 1964, however, there has been a slight but steady decline in the percentage of potash coming from traditional underground operations, largely because of the increasing significance of solution mining. By 1967, the percent of potash coming from normal underground operations had dropped to less than 88 percent of total domestic production.

Most of the sulfur mined in the United States is mined by the Frasch process, a process which is neither surface nor traditional underground but more akin to the methods classified as solution mining. In the earliest year since World War II for which figures are readily available (1950), approximately 87 percent of the sulfur mined in the United States was produced by the Frasch process. This process essentially involves the dissolving of native sulfur from its host rock with superheated steam and pumping it to the surface where it is solidified and refined. Although the sulfur is not really dissolved in the Frasch process, but is melted and pumped out as a fluid, the entire process is much more closely related to solution mining than to any presently useable underground or surface mining method.

From 1950 on, the percent of sulfur produced in the United States by the Frasch process declined rather steadily until 1963, when less than 74 percent of the nation's domestic sulfur production came from such operations. The remaining 26 percent was produced largely as a by-product in the mining of other commodities (both by surface and normal underground methods), from manufacturing processes such as those that extract sulfur from stack gasses, and as a by-product in petroleum and natural gas operations. Since 1963, however, the percentage of sulfur produced in the United States from Frasch process operation has again begun to climb, reaching nearly 77 percent in 1967.

Unlike sulfur, rock salt (sodium chloride) has traditionally been mined in the United States by a variety of methods. Virtually none, however, has been produced by standard surface mining methods. Most surface production of salt comes from the evaporation of highly saline waters either in the ocean and the Great Salt Lake or from brines which are pumped from the earth by standard solution mining techniques.

In 1947, nearly one-fourth of the natural sodium chloride produced in the United States came from underground mines. This proportion held relatively constant until 1957. Since then, there has been a rather steady increase in the proportion of salt produced from underground mining operations.

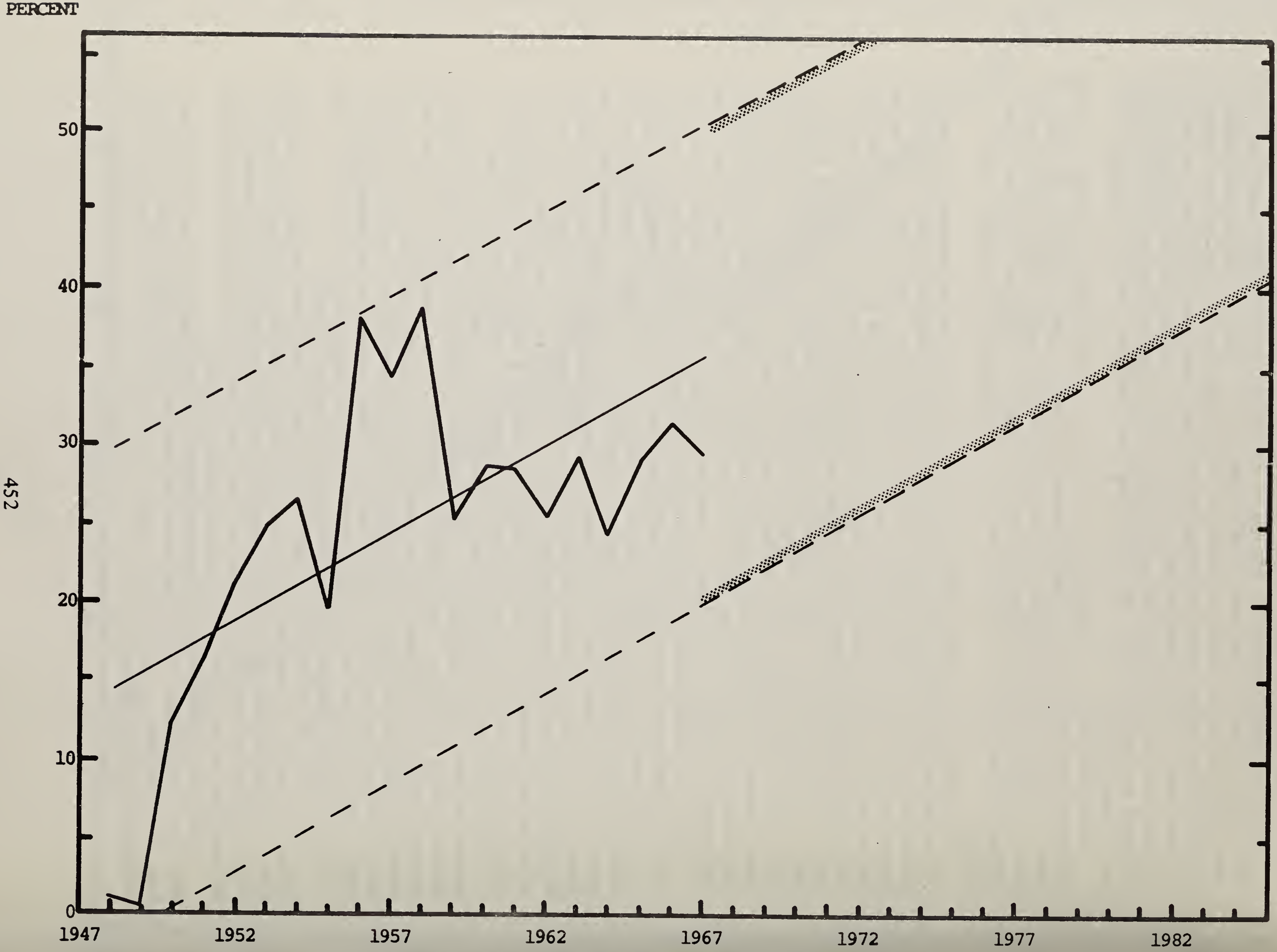


Fig. 64 - Uranium ore mined by surface methods in the United States.

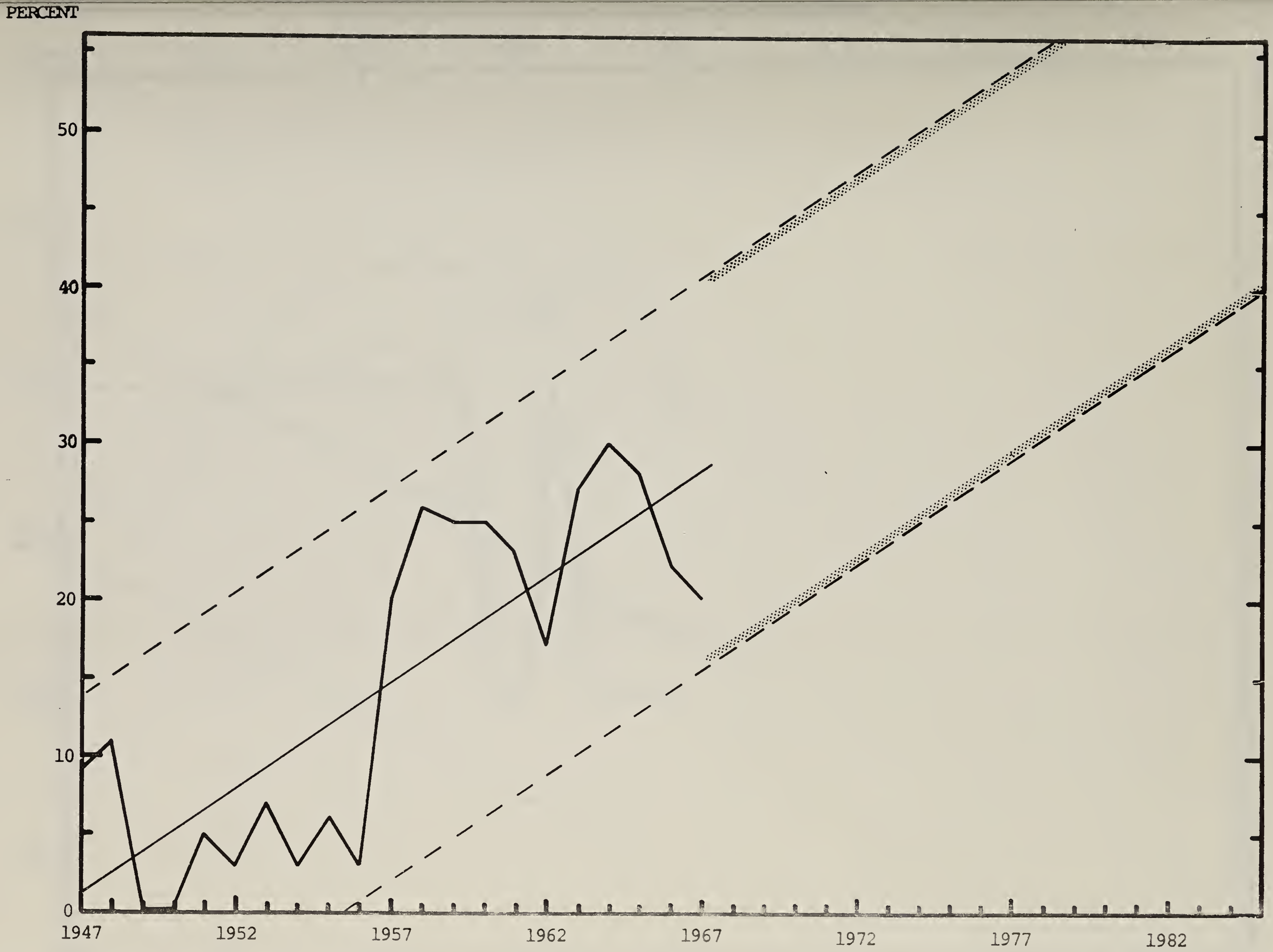


Fig. 65 - Mercury ore mined by surface methods in the United States.

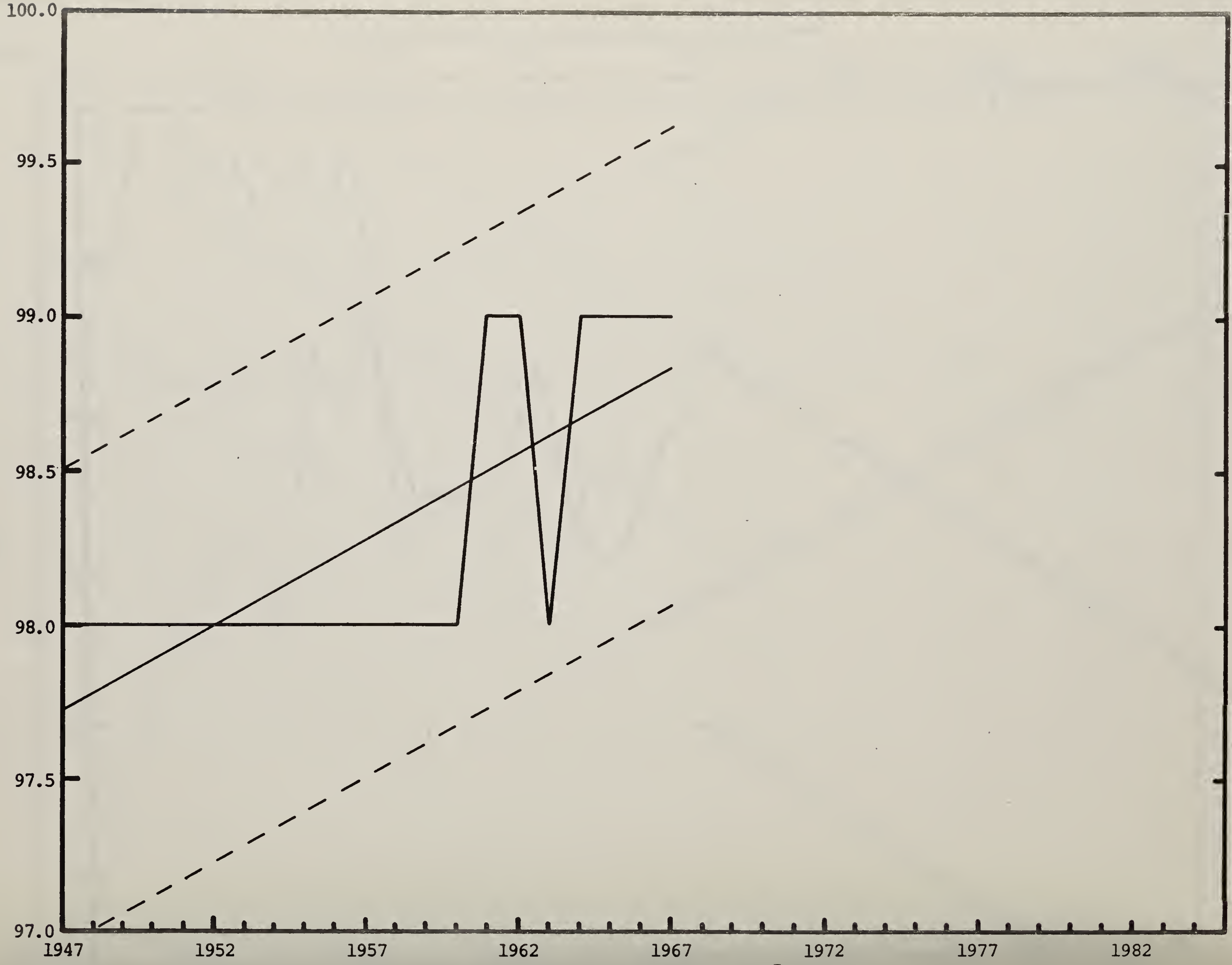


Fig. 66- Phosphate rock mined by surface methods in the United States.

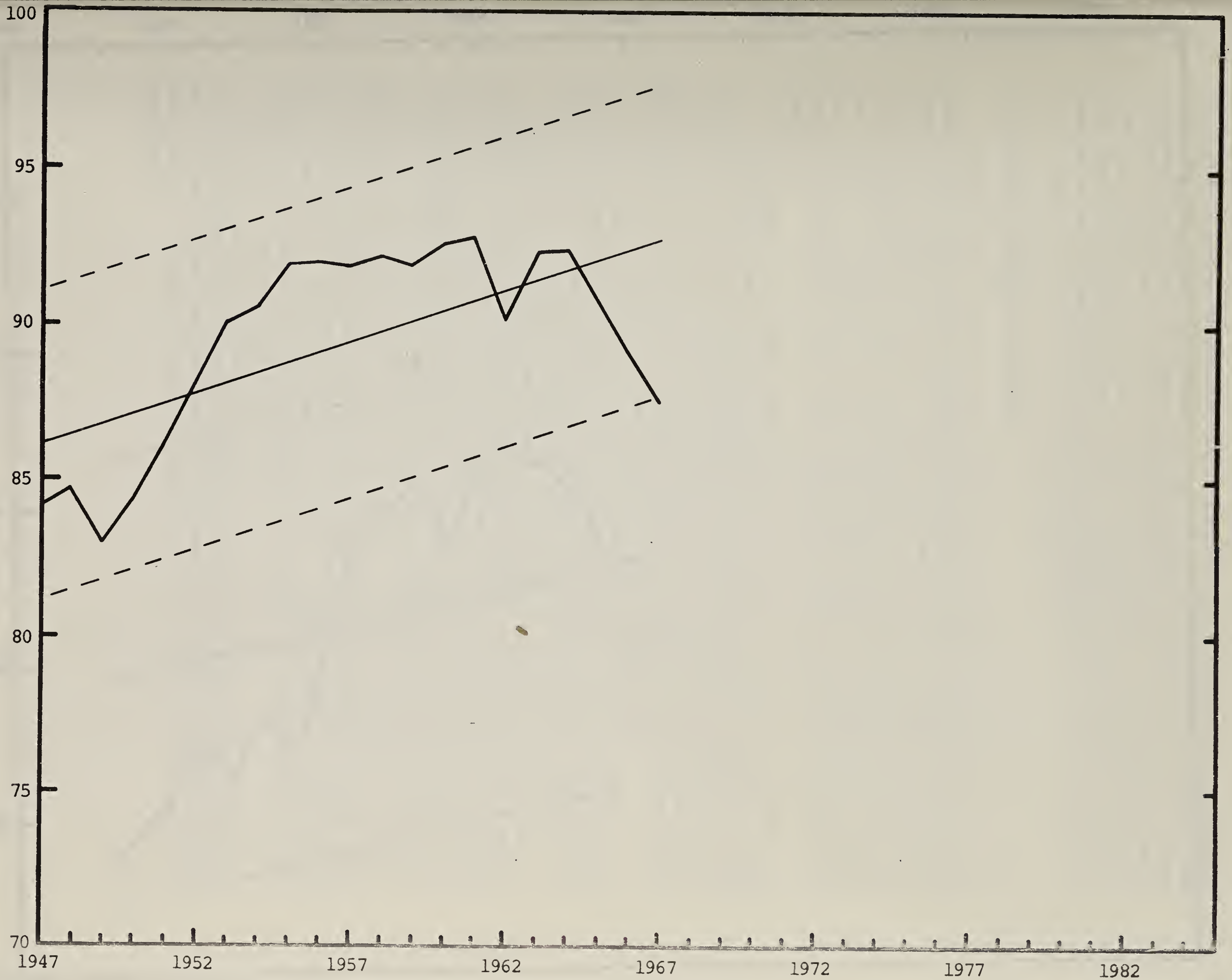
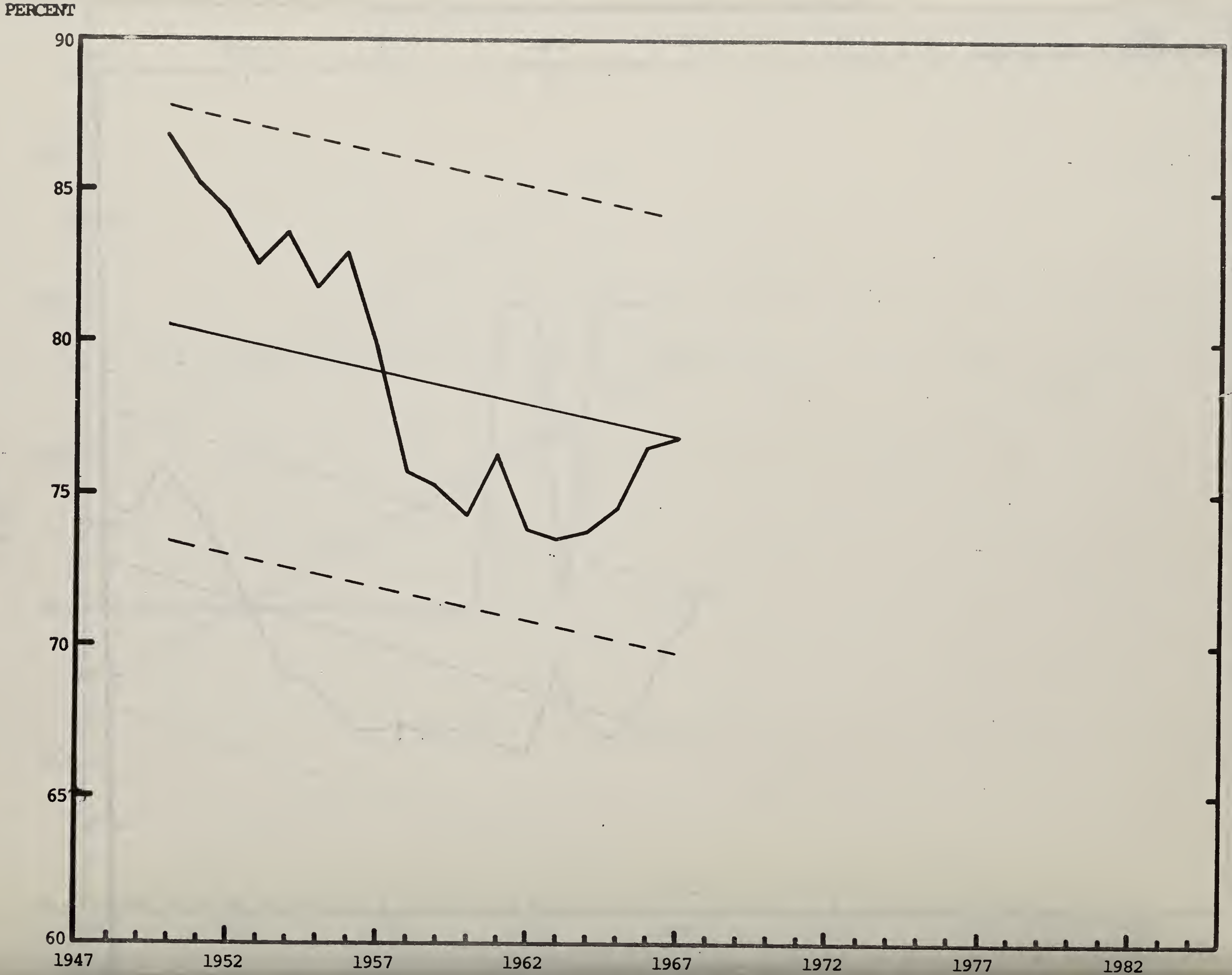


Fig. 67 - Potash mined by underground methods in the United States.


PERCENT
90
85
80
75
70
65
60
1947
1952
1957
1962
1967
1972
1977
1982

In 1967, a high of almost 30 percent of total domestic production from underground operations was reached. This increase apparently came about largely as a result of large increases in the demand for sodium chloride in industrial chemical processes and for greater amounts of sodium metal in ever-changing modern technology. With the production of salt from brine deposits, from sea water, and from the Great Salt Lake limited by the extent of brine deposits and the large space requirements involved in producing salt by evaporation from salt water, the operations most able to expand rapidly and meet the increased demand were the already established underground mining operations.

6. Changes in Beneficiation Operations

Changes have also taken place since 1947 in the beneficiation and advanced processing stages of the nonfuel mineral industries. The changes have come not only in the processes themselves but also is the extent to which they have been used. In copper production, for example, at the end of World War II, four percent of the nation's copper ore went directly to the smelting process without undergoing prior concentration. By the mid-1960's, only one percent of the copper ore mined in the United States was considered direct smelting ore. Conversely, in 1947 about four percent of the copper ore mined was subsequently treated by leaching. By the mid-1960's, the proportion of ore so treated had climbed to ten percent.

The changes in beneficiation technology have been spread throughout the process, and in many respects have been similar to the changes that have taken place in mining operations. The trend in crushing has been to use larger crushers and to increase the number of crushers and crushing stages. Some crushers now in use are able to accept ore feed up to a nominal 60 inches in size. The crushers that have been developed also have greater strength and their parts do not wear out as quickly as they did in the past, because of better alloys. Alloys have been continually improved for crusher strength and wearability.

In the grinding phase of beneficiation, more and larger ball mills and rod mills are now being used. Some plants have found that autogenous mills (i.e., mills in which the large pieces of ore grind the little pieces) are suitable for grinding some ores. Longer-wearing materials such as rubber, alloys, and plastics for mill liners also have been developed.

Froth flotation methods have become almost universally used in the larger base-metal beneficiation plants, replacing the older gravity methods which are now found only in smaller plants. Flotation reagents have been persistently developed to aid known processes and to permit the flotation of an ever wider range of minerals. As high-grade iron ore has become depleted, the lower-grade ores are being beneficiated, largely by magnetic methods.

The conventional gravity, magnetic, flotation, and agglomeration processes which have been in use in beneficiation since before 1947 have been considerably improved. Benefication processes also have come to be used more in series or in specific combinations to produce higher-grade products. Beneficiation equipment has continued to become larger and more efficient. Crushing and grinding units, including antogenous grinders, screens, and other classification equipment, magnetic separators, flotation cells, and agglomeration equipment and plants have all been redesigned or enlarged to process more ore and to produce a purer concentrate at less cost.

Pelletizing has been a significant innovation in the beneficiation of iron ores that has had far-reaching implications. The greater suitability of pellets for blast furnace input has in many instances made lower-grade ores requiring beneficiation more attractive than some high-grade ores, depending of course on other cost factors as well as those involved in beneficiation.

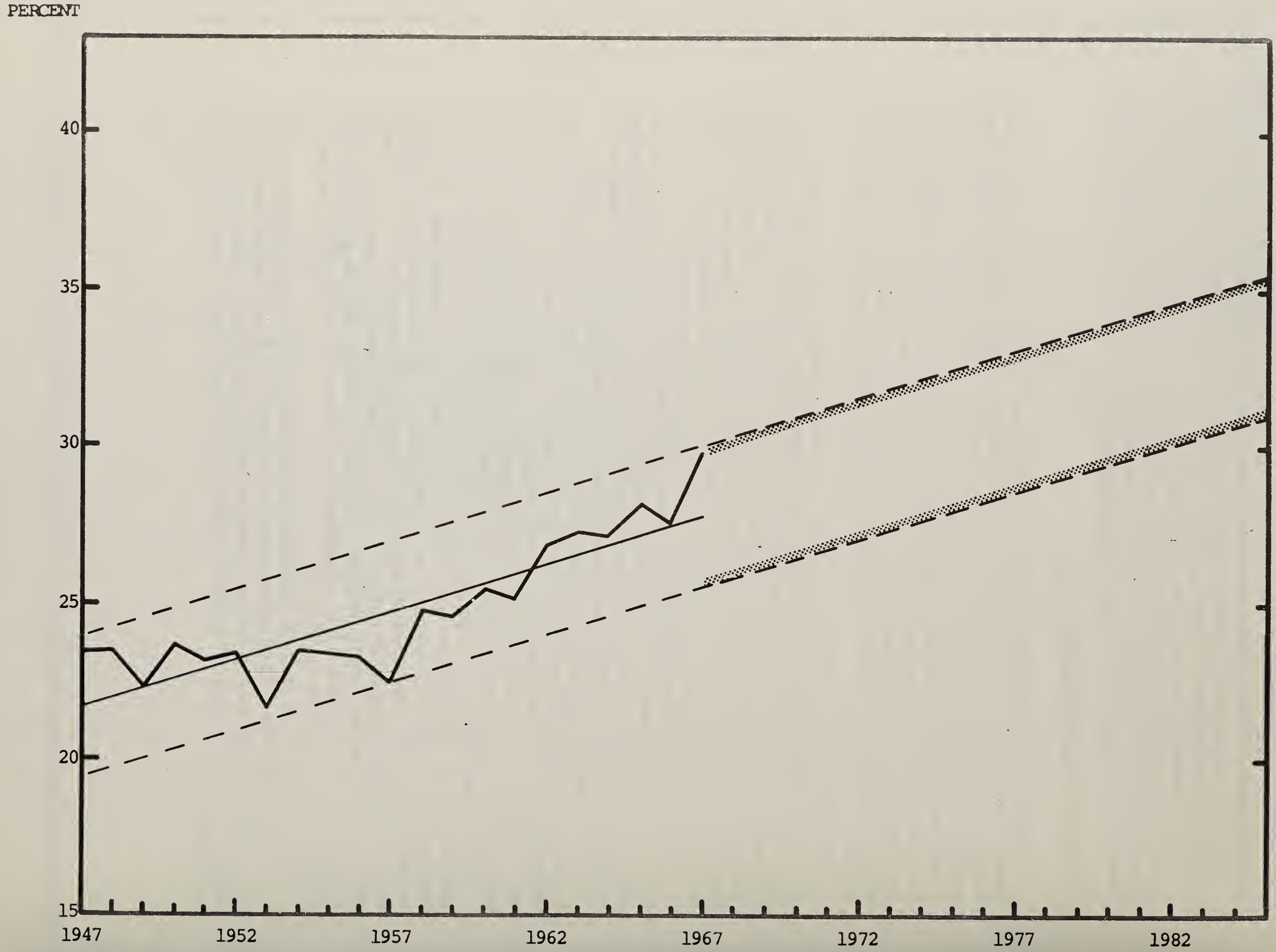


Fig. 69 - Salt mined by underground methods in the United States.

7. Changes in Advanced Processing

In the advanced processing state of minerals production, changes since 1947 have been along similar lines. In iron making, the blast furnace, enlarged and improved over the last three centuries, remains the most efficient tool for processing or smelting iron ore into pig iron. Technologic advances, however, have greatly increased blast furnace capacity in recent years. Blast furnaces capable of producing 1,500 tons of pig iron per day in 1950 could produce 2,700 tons per day in 1963 without any appreciable increase in size. This was accomplished by pressurizing the furnace, improving the hot blast, injecting fuel into the smelting zone, and by using a higher-grade iron ore feed. The higher-grade iron-bearing concentrate was provided by the increased use of beneficiation processes in iron ore production. Sintered or beneficiated and pelletized ore takes less furnace space per unit of iron than does natural iron ore, first because it is higher-grade and second because the higher-grade iron ore requires less limestone, coke, and other agents needed to produce pig iron from iron oxide minerals.

In copper production, improvements have continued since 1947 in extracting copper from its ores by leaching. Solvent extraction of copper from pregnant leach solutions is now used successfully at some plants. Better techniques and equipment for precipitating copper with iron have also been developed. There has been a trend toward the wider employment of leaching as various companies changed this process from a sideline to that of a major part of the copper production operation.

In copper smelting, the older, hearth type roasters have gradually been abandoned. The trend in recent years has been to use a fluidizing roaster to remove sulfur dioxide from the sulfide minerals. This is further processed, where there is a market, to make products such as sulfuric acid and crude sulfur. The development of these processes also prevents large quantities of sulfur dioxide from entering the atmosphere.

Few copper reduction plants still use blast furnances in smelting, with most plants now using reverberatory furnaces adapted to treating fine-grained sulfide concentrates. Larger, better controlled reverberatory furnaces have come into use. Furnace designs and refractory materials used in the furnaces have been improved. In the newer or remodeled plants, larger and better designed converters have also been built with improved refractory materials. The use of control devices has been intensified to help manage the converting process.

In addition to new equipment, new smelting techniques have been developed. The use of green wooden poles for reducing copper oxide in fire refining has given way to other reducing agents such as reformed natural gas and ammonia.[124] Similar innovations have been made in other advanced processing operations, not only in the treatment of metalliferous ores, but also in the preparation of nonmetallic minerals for use as industrial raw materials.

E. CURRENT PRACTICE IN MINERALS PRODUCTION

1. Placer Mining

Today, the method of mining that was responsible for the initial development of mineral resources in the Western United States is almost extinct in that region. Placer mining is presently only of minor importance in the West. Elsewhere, however, such is not the case and placer mining has become in some places as modern and mechanized as other methods of mineral production. In such areas, mobile powered equipment used in placer mining includes track-mounted dozers, draglines, power shovels, and front-end loaders. The bulldozer is usually used in conjunction with the perennial sluice box, the dozer pushing heavy mineral-bearing gravel into the sluice where running water washes out the sand and gravel and the heavy minerals settle out behind riffles. Draglines, shovels, and front-end loaders are usually used in conjunction with portable washing plants which separate the coarse and lightweight waste material from the finer and heavier fractions of heavy minerals. The concentrate produced is transported to a mill for further gravity concentration.

Ground sluicing utilizes the natural flow of water for disintegrating a placer deposit and transporting the dislodged material through a sluice where the valuable heavy minerals are concentrated. Ground sluicing is suitable for small-scale mining, but it requires a large water supply and a suitably located deposit. When the supply of water is insufficient for continuous operation, storage reservoirs are constructed from which a satisfactory volume of water can be released periodically through gates. Sluicing has been used extensively in the subarctic regions for stripping overburden from small deposits.

Hydraulic mining is similar to ground sluicing except that the water is delivered under substantial pressure. The principal requirements for hydraulic mining as currently practiced are several. The mineral material in place must be amenable to disintegration by the action of water under pressure. There must be an adequate supply of water that can be delivered under a pressure sufficient for the purpose, generally the higher the better. There must be adequate space for disposal of debris. Of critical importance is the susceptibility of the mineral of interest to efficient concentration in a sluice box, under the variable conditions of pulp density and rate of flow that occur in a hydraulic system. There must also be sufficient natural grade to permit the maintenance of hydraulic slope as the mining face is advanced, for the installation of sluice boxes to concentrate the mineral, as well as for the disposal of tailings in the natural channel or beyond the discharge point of an elevator. But perhaps the most important requirement of all (and the factor that has been absent in the Western States) is the absence of, or minimal influence of, regulations governing the introduction of solids into streams and the deposition of debris.[125]

In present-day hydraulic mining, water under pressures of around 100 pounds per square inch is delivered through a special nozzle called a hydraulic *giant* that is connected to the supply line by a semi-universal joint. The high-pressure stream of water coming from the hydraulic giant is directed against a bench, disintegrating and washing the material downgrade to a sluice box. Auxiliary equipment may include hydraulic elevators, gravel pumps, elevated sluices, and the mechanical equipment used to stack tailings. Hydraulic mining has proved to be the only practical method so far devised for large-scale removal of the vast deposits of frozen muck that overlie most of the auriferous gravel deposits found in Alaska and the Yukon.[126]

Dredging is an important placer mining method that is still in wide use in many areas for both construction and the production of sand and gravel. Strictly defined, dredging is the underwater excavation of mineral deposits using a floating contrivance called a dredge. The term is sometimes applied, however, to underwater excavation where land-based machines such as draglines or slackline bucket scrapers are used.

As used today, a floating dredge is a large raft or barge on which are mounted excavating equipment and (in metal mining) a gravity concentration system. Material is excavated at

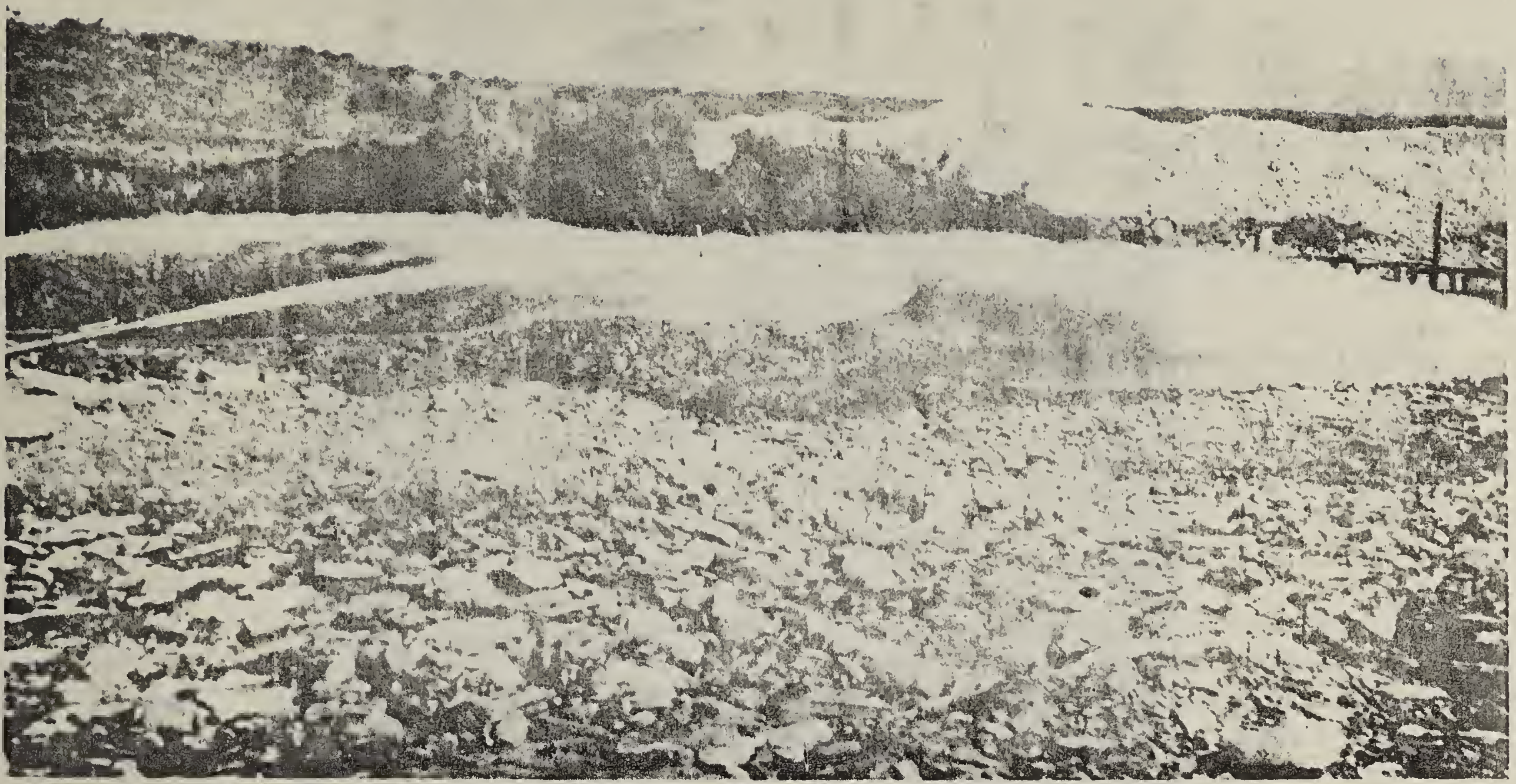


Fig. 70 - Ground sluicing is still used in some parts of the world, including Alaska, but is now virtually unknown in the 11 Western States. Appropriate for small placer operations, the method requires abundant water. (Photo courtesy of Arizona Pioneers' Historical Society)

the forward end by buckets or suction pumps, then elevated, washed, screened, and concentrated for the recovery of any valuable mineral present. The oversize and other wastes (called tailings) are discharged to the rear of the dredge by a stacker.

Several factors govern the physical applicability of the bucket-line dredge. There must be an adequate water supply in relation to the character of the material mined, particularly with respect to the percentage of clay or slime in the ground. The character of this material mined is also important, as are the size and number of boulders in the gravel and the presence of any buried timber or vegetation. Surface topography in relation to groundwater level and surface grade is also of critical import, as is the size and shape of the area to be mined, particularly its minimum width. The depth of the deposit, the topography on top of bedrock, and the character of the bedrock itself must also be considered. Likewise to be taken into account are the overburden, the type and amount of vegetation that must be cleared from the surface, the range of fluctuation in the water level (in rivers and lakes), the climatic conditions that determine the length of an operating season, and if offshore, the depth of water, storm and current conditions, and the character of sea floor.[127]

Dredging is generally adapted to large, thick deposits containing enough gravel to warrant the large initial investment required for testing the ground and for purchasing and erecting expensive dredging equipment. Placer dredges have been built with buckets ranging from 1.5- to 20-cubic-foot capacity, but the usual range is from six to 16 cubic feet. Digging depths below water level have been from as little as eight feet to over 100 feet. The weight of conventional dredges ranges from 125 to 175 tons per cubic feet of bucket capacity.

In 1936, 66 percent of the total gold recovered from placers in the United States was produced by floating dredges of the connected-bucket-ladder type. That same year, there were 38 dredges operating in Alaska, 45 in California, 12 in Idaho, five in Oregon, two in

Fig. 71 - Hydraulic mining is still used in Alaska but not in other Western States. The method involves the extensive use of water under pressure and creates problems in fluid waste disposal in some areas. (Photo courtesy of Arizona Pioneers' Historical Society)

Montana, and one in Colorado, a total of 103 for the entire country. These dredges recovered more than 600,000 fine ounces of gold that year. Today the amount of such gold dredging is of minor importance in the United States.[128]

2. Underground Mining

While placer mining has virtually disappeared as a significant mineral production method in the United States (primarily because of the legal restrictions placed upon its environmental effects), underground mining methods have remained important. They have done so in spite of technological advances in surface mining methods and the increasing costs and complexities inherent in underground operations. As shown in Table 32, there remains a substantial variety of mineral commodities being produced from large underground mines. An even greater variety is produced from smaller underground operations. While underground mining's share of the total production of various commodities such as copper and iron ore has declined, other materials still rely heavily on underground mine production. Nearly all of the lead, zinc, potash, trona, mercury, tungsten, about two-thirds of the molybdenum, and about half of the uranium and gold produced in the Western United States are mined underground. In addition, nearly all primary (non-by-product) silver mined in the country is produced from underground mines.

At the present time, a wide variety of underground mining methods are in use. Each has its own particular characteristics regarding costs, space requirements, and suitability for particular mineral deposits and mineral commodities. Some mineral deposits formed through various sedimentary, metamorphic, and igneous processes, including many disseminated copper deposits, are mined largely by open pit methods. Veins and massive replacement deposits, however, are usually mined by underground methods as are some disseminated orebodies. Whether a mineral deposit is mined by surface or underground methods (and in turn by what type of underground method) depends, however, on the size and shape of the orebody, its proximity to the surface, and the amount and character of overburden or adjacent waste rock which must be removed, and not necessarily on the geologic classification into which the deposit falls. Although the lead and zinc deposits of Missouri occur in discontinuous clusters extending over hundreds of square miles, they are too deep to be minedby anything but underground methods at the present time.

The competence of the orebody host rock and adjacent rocks, the dimensions of the orebody, and its attitude are the most important factors in determining the type of underground mining method used in current practice. For some mineral deposits, every opening in the rock must be artificially supported. In others, the rock is such that natural support methods can be used. In still a third class, the character of the ore and adjacent (usually overlying) rocks is such that its natural tendency to collapse when left unsupported can be utilized in the mining system.

Artificial support stoping methods form the highest-cost, least productive class of underground mining methods, and are therefore applicable only to fairly high-grade ore deposits. Artificial support methods may be most economical, however, when unsupported stopes cannot be used because weak ore, waste, or both will not stand unsupported, or if the presence of very high grade ore makes natural support uneconomical because of the high values left in the unmined pillars.

One of the most commonly used methods involving artificial support is *shrinkage stoping,* in which ore is commonly removed in ascending horizontal slices with most of the broken ore being left in the stope to support both the walls and the miners while they prepare to excavate the next slice (see Figure 72). When drilling and blasting work in the stope is completed, the remaining ore can be withdrawn. This method is most commonly used in steeply dipping vein or bedded deposits of competent ore. Moderately weak wall rocks can be tolerated, as the broken ore provides some lateral support.

While shrinkage stoping is the least costly of the supported stope methods, it has two important disadvantages. Because most of the broken ore is retained in the stope until

Table 32

THE LARGEST UNDERGROUND MINES IN THE UNITED STATES, 1967[a]

Mine	Company	Commodity	Principal Mining Method	Ore Mined (millions of tons)
1. Climax (Colorado)	American Metal Climax, Inc.	molybdenum	block caving	15.381
2. San Manuel (Arizona)	Magma Copper Company	copper	block caving	14.391[b]
3. White Pine (Michigan)	Copper Range Company	copper	room-and-pillar	6.850[b]
4. Carlsbad (New Mexico)	Southwest Potash Corporation	potash	room-and-pillar	3.158
5. Federal (Missouri)	St. Joseph Lead Company	lead	open stoping, casual pillar	2.932
6. Pea Ridge (Missouri)	Meramec Mining Company	iron	caving methods	2.639
7. Mather (Michigan)	Cleveland-Cliffs Iron Company	iron	sublevel stoping	2.126
8. New Mexico Potash	Kerr-McGee Corporation	potash	room-and-pillar	2.094
9. Grace (Pennsylvania)	Bethlehem Mines Corporation	iron	block caving	1.913
10. Homestake (South Dakota)	Homestake Mining Company	gold	cut-and-fill	1.899
11. Viburnum (Missouri)	St. Joseph Lead Company	lead	open stoping, casual pillar	1.804
12. Westvaco (Wyoming)	Federal Resources Corporation	trona	room-and-pillar	1.600
13. Cornwall (Pennsylvania)	Bethlehem Mines Corporation	iron	caving methods	1.534
14. Belle Isle (Louisiana)	Cargill, Inc.	salt	room-and-pillar	1.151
15. Saunders (New Mexico)	Duval Corporation	potash	room-and-pillar	1.070

[a] Nonfuel minerals only.

[b] 1966 production is shown because of a prolonged strike in 1967.

Source of data: *World Mining, Catalog, Survey and Directory Number,* Vol. 4, No. 7, June 28, 1968, pp. 122-123.

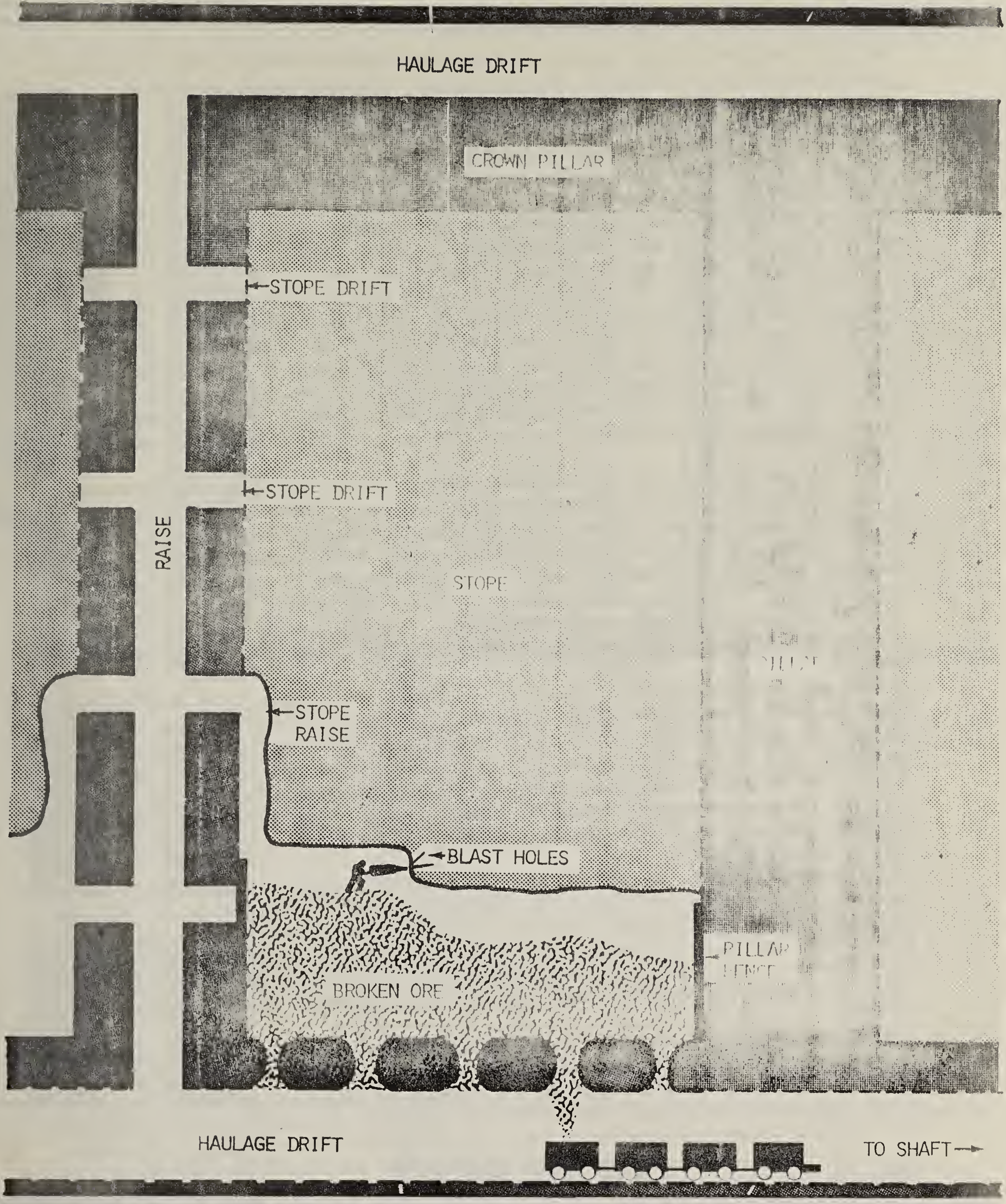


Fig. 72 - Idealized section of a shrinkage stope in a steeply dipping vein or bed. As excavation progresses upward, the broken ore supports both the miners and the walls. The difference in volume between the ore in place and broken is the "shrinkage" which is drawn off after each cycle. Costs are high.

mining is complete, capital recovery is delayed. In addition, broken sulfide ores tend to oxidize while lying in the stopes, thereby adversely effecting beneficiation efficiency and creating a fire hazard from the heat generated by the oxidation process.

The usage of shrinkage stoping has declined in recent years in the United States in favor of the *cut-and-fill* method, mainly because the latter technique does not involve the necessary long-term storage of broken ore in working stopes. Furthermore, the cut-and-fill method allows a significant portion of the waste created in mining and beneficiation to be re-stored underground and not spread out over the surface. As shown in Figure 73, the method makes effective use of waste material by putting it back into previously excavated areas in order to maintain the position of the surrounding rock.

Cut-and-fill stoping, like shrinkage stoping, is characterized by the extraction of horizontal ore slices in an ascending sequence. In cut-and-fill mining, however, after a slice of ore has been broken and removed from the stope, a layer of waste rock (or mill tailings) equal in volume to the removed ore slice is placed in the stope. This waste fill performs the same function as the broken ore in the shrinkage stope. It provides support for weak wall rocks and for mining activity in extracting the next slice. Cut-and-fill stoping is applicable to steeply dipping vein or bedded deposits of strong ore that have moderately weak to weak wall rock.

A variety of materials can be and are used for fill material in cut-and-fill stopes. The most common is concentrator tailings from beneficiation operations on the surface. This material is pumped into the stope in slurry form, and after the water is drained off, the remaining surface becomes firm and level. The addition of cement to the top few inches of the slurry fill layer results in a strong floor capable of supporting mechanized mining equipment. Overlaying the fill material with steel plates provides the same capability. Also, by using occasional stulls, rock bolts, or gunite sprays, cut-and-fill mining can be extended to deposits of moderately weak ore, thereby encroaching on the domain of the timber-support methods.

In addition to broken ore and waste, timber is still used to support the walls and back (roof) in many underground mining operations. Two general types of timbered stopes are used, *stull stopes* and *square-set stopes.* Where small, thin veins are mined and only temporary wall rock support is required, single timber props, or *stulls,* may be wedged between the hanging and foot walls. *Stull stoping* is a simple method for small vein deposits, requiring little capital investment and therefore is favored by the small miner. Indeed, the declining usage of stull stoping has paralleled the decline in the number of small underground metal mines.

In *square-set stoping,* the timbers are erected in a three-dimensional lattice work of roughly cubical frames (see Figure 74) enabling larger deposits to be mined. As with shrinkage stoping, the direction of mining is normally upward, but usually only enough ore is broken to permit another *set* to be installed. This is because square-set stoping is only used in weak ore that requires immediate support. For stronger ore, another mining method would be selected, for square-set stoping is the most expensive of the underground mining methods.

Square-sets alone provide only temporary support, and waste is commonly used to fill the lower sets for permanent support. Ore passes and manways, of course, are maintained from the haulage drift up through the fill material for access to the active stope area. Increasing timber costs and the large amount of non-productive labor involved in preparing and installing timbers has resulted in the declining use of timbered stopes. Nevertheless, there will undoubtedly continue to be limited usage of timbered stopes for deposits of high-grade, weak ore where no other method is applicable.

Of the three artificial support methods, only cut-and-fill mining has expanded its range of application in recent years. The reason for this expanded usage has been the amenability of cut-and-fill stoping to the higher productivity mining equipment and techniques developed recently. The opportunity of underground disposal of a portion of the waste material produced in beneficiation operations has also become more attractive.

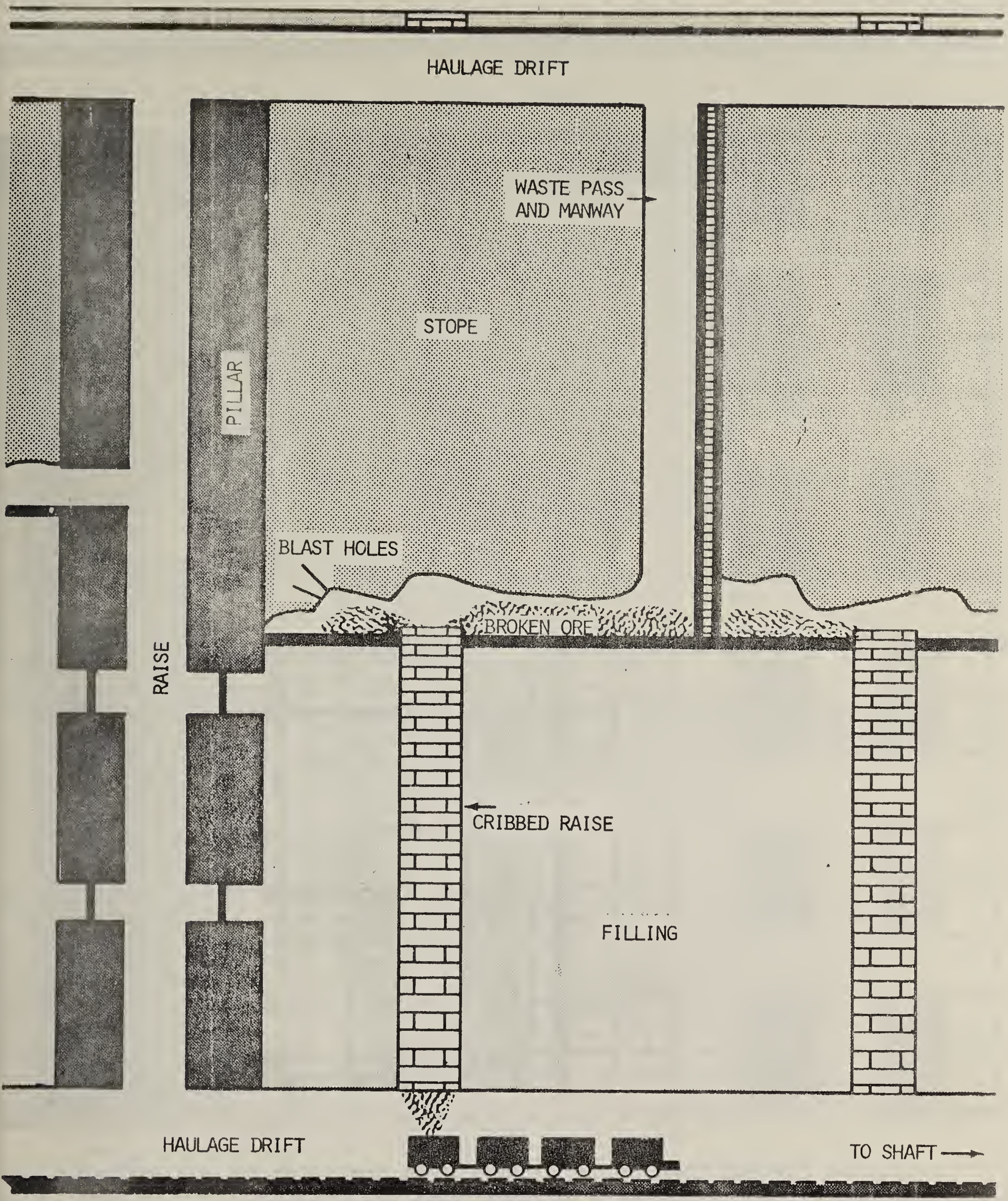


Fig. 73 - Cut-and-fill stoping involves replacing removed ore with waste material, usually the residue from beneficiation operations. It is costly and requires high-grade ore and specific geologic conditions.

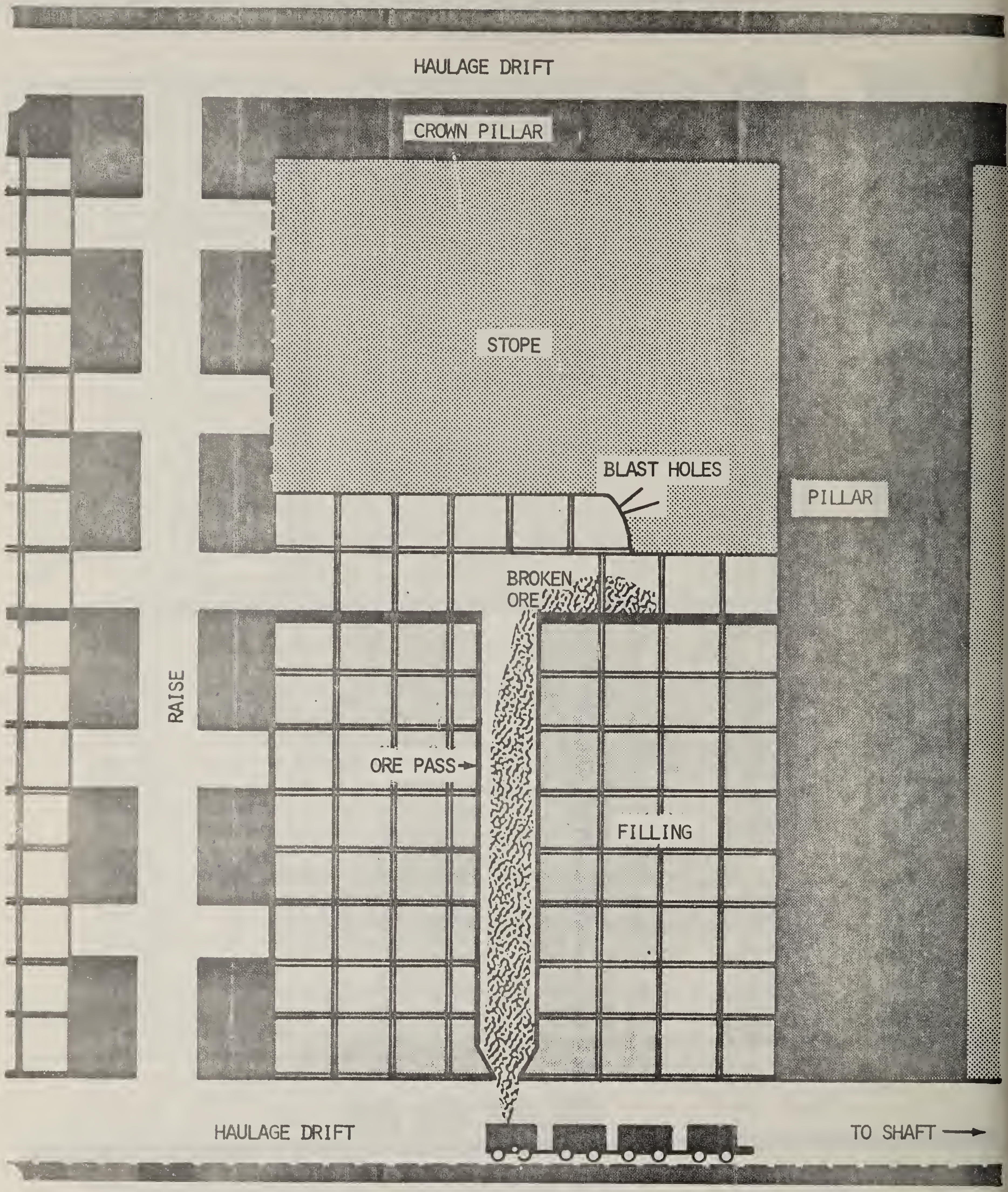


Fig. 74- Square-set stoping uses extensive timbering to provide temporary support in active workings. The most costly of all underground methods, it requires large amounts of wood and manpower, and ore must be of particularly high grade to warrant its use.

Natural support or *open stoping* methods are generally considered to be restricted to competent rock formations, as roof support is usually provided only by natural pillars. The *back* is thus required to be self-supporting between pillars. An obvious exception to this generalization is room-and-pillar coal mining (a natural support method) where a very weak material, coal, is mined. In this application, however, stulls normally provide temporary support between the pillars, which themselves are often mined on retreat, allowing the entire back to cave after operations have been finished. This of course, produces some surface subsidence.

Stope-and-pillar and *room-and-pillar* are closely related mining methods that are normally used in deposits having many similar characteristics. Both methods involve mining by excavating "rooms" or stopes and leaving adjacent rock in place as natural pillars to provide overall roof support.

The stope-and-pillar method is normally applicable to fairly horizontal, tabular or bedded deposits of large lateral extent, but in which the actual ore is distributed irregularly and the size of the individual orebodies is variable. This irregular distribution of ore values inhibits long-term planning for pillar sites, for the logical pillar locations are, whenever possible, in waste rather than ore. Consequently, the plan view of a stope-and-pillar mine often suggests random pillar locations, whereas these locations are actually selected very carefully to maximize ore extraction and mine safety.

In the room-and-pillar method, pillars are left on a regular predetermined pattern facilitating high speed, rapid advance mining. As with stope-and-pillar mining, the room-and-pillar method requires a large bedded or tabular deposit, but one with ore values distributed uniformly throughout the deposit. The regular placement of pillars is practiced only if the ore in the proposed pillars is of no more value than ore in the excavated rooms. While room-and-pillar mining is most widely used in coal mining, it is also used frequently in other large, bedded, uniform, low-grade deposits such as potash, salt, and native copper. In coal mining, a large portion of the total production in a typical room-and-pillar operation today comes from pillar mining on retreat, or second mining.

While the stope-and-pillar and room-and-pillar mining methods used today are quite similar in their overall characteristics, they are normally considered as distinct methods because their primary areas of application are quite different. Stope-and-pillar mining is most widely used in "hard rock" mining, the most famous example being the Tri-State and Southeastern Missouri lead belts. Room-and-pillar mining has been used mainly in "soft" rock mining such as at Carlsbad, New Mexico, and has permitted the development of high-production continuous mining systems where ore is broken by continuous mining machines rather than intermittently as in the drill and blast cycle used in most other forms of mining.

While the two open stoping methods just mentioned are applicable to horizontal, tabular deposits, *sublevel open stoping* is used with a steeply dipping or massive orebody with a long vertical dimension. Both ore and waste rock must be strong and must stand well without caving over long periods. In sublevel open stoping, a vertical slot is excavated, usually in the middle of the stope-to-be, and the ore is then mined in vertical slices drilled from the sublevels and blasted into the open slot. The ore falls to the lower haulage level where it is drawn off through chutes into ore cars for haulage to the hoisting shaft.

Sublevel open stoping offers low operating costs, but it is hampered by the large amount of pre-production time and capital required in driving the large number of development openings. Another restriction of the use of this method is the need for both strong ore and strong wall rock. Because of the large open stopes created, strong rock is required to prevent caving, ore dilution, and surface subsidence.

With some ore deposits it is either impossible or undesirable to prevent overburden waste rock from caving in after the ore has been removed from beneath it. In contrast to the open stope mining methods, the success of the four principal caving methods depends on the caving of the back almost immediately after support is removed. A characteristic result of these methods is surface subsidence once the caving action reaches the surface. The caving methods require large, steeply-dipping or massive, uniform, and fairly low unit value deposits, as these methods generally are the least selective mining methods currently in use. With the exception of top slicing, they are most susceptible to ore dilution from waste rock.

Top slicing is a relatively high-cost caving method that was widely used in the high-grade hematite mines of Upper Michigan, but is seldom used today. Because of its comparatively high cost, top slicing is now used only where extremely poor ground conditions, i.e., extremely weak overburden and weak ore, are encountered. In top slicing, the ore is excavated in horizontal slices in descending order from the top of the orebody. Each production slice drift is heavily timbered to temporarily support the back until the ore in that drift is removed. Then the drift floor is covered with planking, and the overburden is allowed to cave. The layer of wooden timbers and planks that develops between the ore and the overlying waste is called the *mat.* The mat prevents dilution of ore with waste, and also makes the back somewhat easier to support during the mining of succeeding underlying slices. Low productivity, high timber costs, and an extreme fire hazard from the large quantity of timber used have nearly eliminated the use of top slicing today. It is, however, still used to extract high-grade pillars in some open stope mines.

Sublevel caving is closely related to top slicing, but requires stronger ore. In this method, sublevels are caved in alternate horizontal slices, and the ore in that slice and the ore immediately above are removed. Historically, sublevel caving has been only slightly more economical than top slicing and would, therefore, probably be seldom used today except for the unique version of sublevel caving developed in Sweden. At the Kiruna iron ore mine in Northern Sweden the ore is very competent, but the hanging wall is weak. The strong ore has permitted large openings to accommodate large mechanized mining equipment, thereby reducing sublevel caving's mining costs to a competitive level. Ore is thus broken cheaply, and the weak hanging wall is allowed to cave. The Swedish variation of sublevel caving may expand the applicability of this method to other ferrous or industrial mineral deposits where strong ore and weaker waste rocks might be encountered. The method is only rarely used in the Western United States at present.

Longwall mining is the most widely used coal mining method in Europe, but it is much less frequently employed in North America. Deposit requirements are similar to those for room-and-pillar mining, i.e., a fairly horizontal bedded deposit, of large lateral extent, with a uniform value. Longwall mining is, however, applicable at greater depths (i.e., high rock stresses) than room-and-pillar because the back is allowed to cave in longwall mining. This is one of the main reasons that the method is extensively used in Europe, while the shallower American coal beds have been more economically suitable for room-and-pillar mining.

In longwall mining, a long face (usually 500 to 100 feet long) is advanced uniformly without leaving pillars, and the back is allowed to cave a very few feet behind the working face. Temporary roof supports, often hydraulic jacks, protect the face area during mining and are advanced as each vertical ore slice is removed from the face. In soft rock deposits, excavation is usually done with a continuous mining machine that eliminates the drill and blast cycle and breaks and loads ore continuously.

The hard rock applications of longwall mining to date have been limited to uranium, manganese, and (experimentally) to copper. However, as continuous mining methods for hard rock are developed in the future, the low mining costs and minimum amount of development required for longwall mining should encourage more widespread usage of this method. A direct consequence of longwall mining is surface subsidence.

Massive, low-grade, well-fractured orebodies are amenable to *block caving,* the underground mining method currently having the lowest unit operating costs. Block caving operations vary in size from medium to high tonnages at low cost, and some block caving mines are competitive with surface mining methods on an operating cost basis.

In block caving, a large block of ore is undercut by removing a horizontal layer of rock under the block. Then, because of its own weight, the weak ore begins to break up and cave into the opening below, where it is drawn off into ore trains. Obviously, one of the primary advantages of block caving is that most of the ore is broken by the force of gravity, and

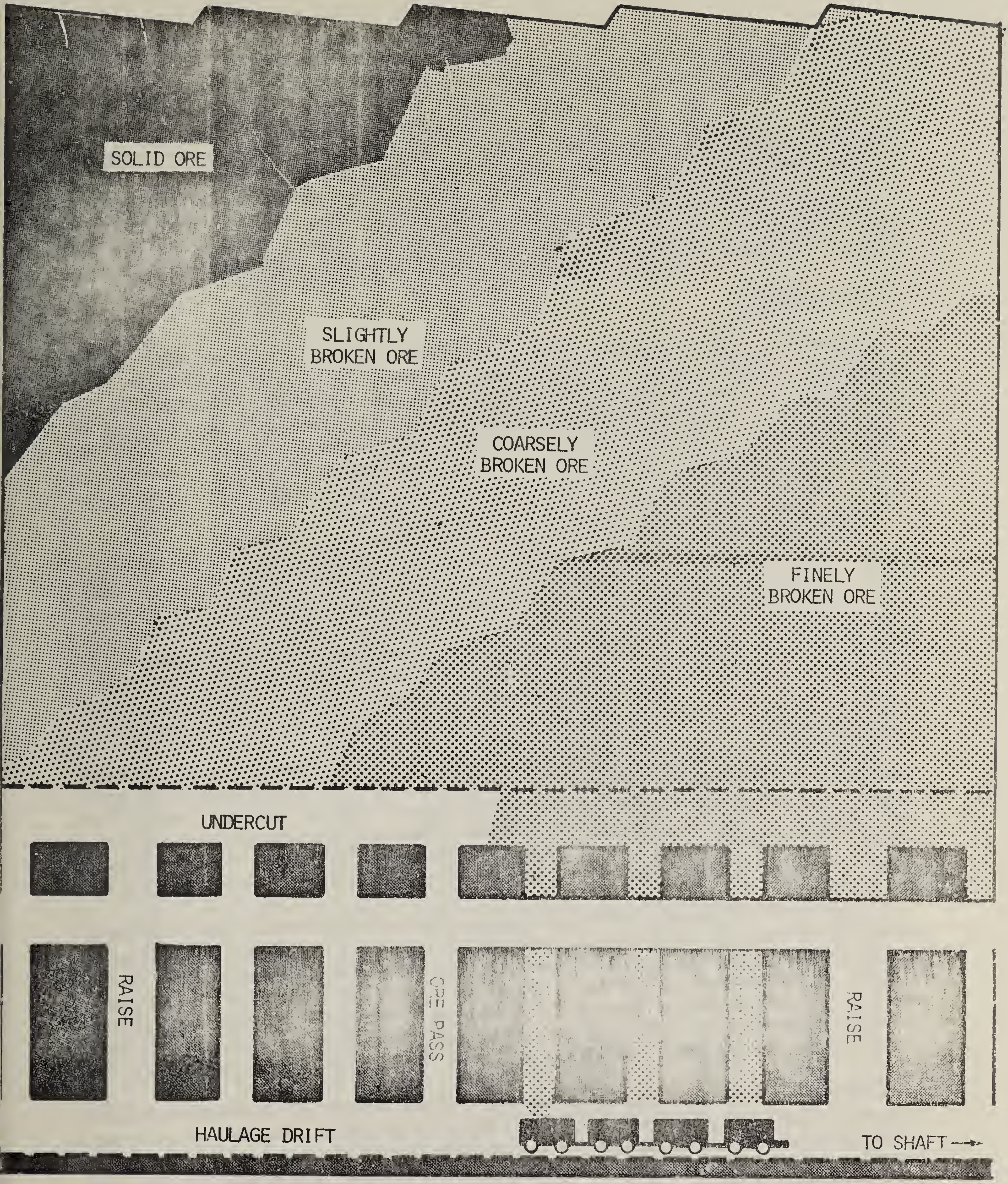


Fig. 75 - Block caving is the cheapest of all underground mining methods, but it requires a large, regular orebody composed of rock that will collapse and break up when its natural support is removed.Normally, considerable surface disturbance ensues.

drilling and blasting are used extensively only in development excavations. The ore caves all the way to the surface where a sizeable subsidence crater grows progressively larger as mining continues.

As can be seen from the drawing of a typical block caving mine in Figure 75, there is extensive pre-production development required with this method. Block caving is also the least selective mining method (waste inclusions in ore must normally be mined as ore) and is most susceptible to ore dilution with waste. When the geologic and economic conditions are favorable, however, block caving offers comparatively low operating costs and relatively high productivity to the underground mine operator. It is now used at both Climax and San Manuel in the West, at several iron mines in the East, and even in asbestos mining in Canada.

3. Surface Mining

Perhaps the most commonly used mining method existing today, and certainly the most noticeable, is *open pit mining.* An open pit mine is a mine broadly open to the surface. The excavation is ordinarily made from the surface downward with a series of benches 30 to 50 feet in height. For this reason, open pit mining is sometimes referred to as bench mining. In order to provide working room, the bench width must ordinarily be a minimum of 50 to 100 feet. Working slopes are often as flat as 25 degrees, whereas final slopes are sometimes steeper than 45 degrees. To reduce the amount of advance stripping, the slopes are carried as steeply as possible without unduly restricting operating room.

One of the most symmetrical open pits in existence today is the New Cornelia pit of the Phelps Dodge Corporation at Ajo, Arizona, shown in Figure 76. Others in the West are usually not of such regular dimensions, as shown by the view of the pit at Ray, Arizona, shown in Figure 77. Still others (and many are included in this category) are not even pits at all in the sense that they have been excavated below the surrounding surface of the land. Many have been formed by digging into hillsides and removing part or all of a previously existing mountain. The open "pit" mine of the Hanna Mining Company near Riddle, Oregon, is of this type. There, the mine has been formed by scraping off the top of the mountain. Even the largest of the open pits, Bingham Canyon, was at least originally a hillside operation.

While the choice between underground and open pit mining is based largely on geologic criteria, once the selection of the open pit method for mining a mineral deposit has been made, the detailed characteristics of the pit are based more on economic factors. The determination of final pit limits and the ultimate outline of the pit are governed largely by economics. The pit will normally be expanded outward and downward to the break-even point, i.e., to where additional stripping and mining cannot be paid for by the values in the ore recovered.

Several factors determine the break-even point. The unit recoverable value of the ore is influenced by the grade of the ore, mill and smelter recovery rates, and the selling price of the product. A reduction in any one of these will reduce the break-even point and shrink the ultimate size of the pit. An increase in any of the costs of production, such as ordinarily occur as mining gets deeper (because more and more energy must be expended in getting each unit of production to the surface), without offsetting decreases in other production costs, will decrease the break-even ratio and likewise reduce the size of the orebody and the pit.

Ordinarily as a pit gets deeper, an increasingly larger amount of overburden must be removed for each ton of ore mineral, simply because of geometry. Therefore, the unit cost of stripping (cost of stripping per ton of ore), like that of ore removal itself, tends to increase with depth. All of these aspects (unit recoverable value, unit production cost, and unit stripping cost) act in concert with the other factors to establish a break-even point in any open pit operation that will fix the final limits of a pit. As these aspects change, so also do the "final" limits of a pit change. What may be considered final under one set of conditions may thus be far from final under another set.

Table 33

THE LARGEST OPEN-PIT MINES IN THE UNITED STATES IN 1967

Mine	Company	Commodity	Waste Stripped (millions of tons)	Ore Mined (millions of tons)	Total Material Handled (millions of tons)
1. Bingham (Utah)	Kennecott Copper Corporation	copper	66.305	33.478[b]	99.783
2. Peter Mitchell (Minnesota)	Reserve Mining Company	iron	6.115[a]	30.527	--
3. Erie Commercial (Minnesota)	Erie Mining Company	iron	19.762	29.700	49.462
4. Morenci (Arizona)	Phelps Dodge Corporation	copper	28.808	19.325[b]	48.133
5. Berkeley (Montana)	Anaconda Company	copper	41.319	15.852[b]	57.171
6. Eagle Mountain (California)	Kaiser Steel Corporation	iron	34.860	12.026[b]	46.886
7. Empire (Michigan)	Cleveland-Cliffs Iron Company	iron	508	10.500	11.008
8. New Cornelia (Arizona)	Phelps-Dodge Corporation	copper	14.910	10.487[b]	25.397
9. Pima (Arizona)	Pima Mining Company	copper	41.000	9.914	50.914
10. Ray (Arizona)	Kennecott Copper Corporation	copper	17.826	8.758[b]	26.584
11. Chino (New Mexico)	Kennecott Copper Corporation	copper	23.078	8.160[b]	31.238
12. Payne Creek (Florida)	Agrico Chemical Company	phosphates	17.723	8.154	25.877
13. Lee Creek (North Carolina)	Texas Gulf Sulphur Company	phosphates	19.000	8.000	27.000
14. Liberty, Tripp, Veteran (Nevada)	Kennecott Copper Corporation	copper	25.398	7.585[b]	32.983
15. Yerington (Nevada)	Anaconda Company	copper	9.732	7.212[b]	16.944

[a] cubic yards.

[b] 1966 production is shown because of prolonged strike in 1967 or because more recent data were not available.

Source of data: *World Mining, Catalog, Survey, and Directory Number*, Vol. 4, No. 7, June 28, 1968, pp. 124-125.

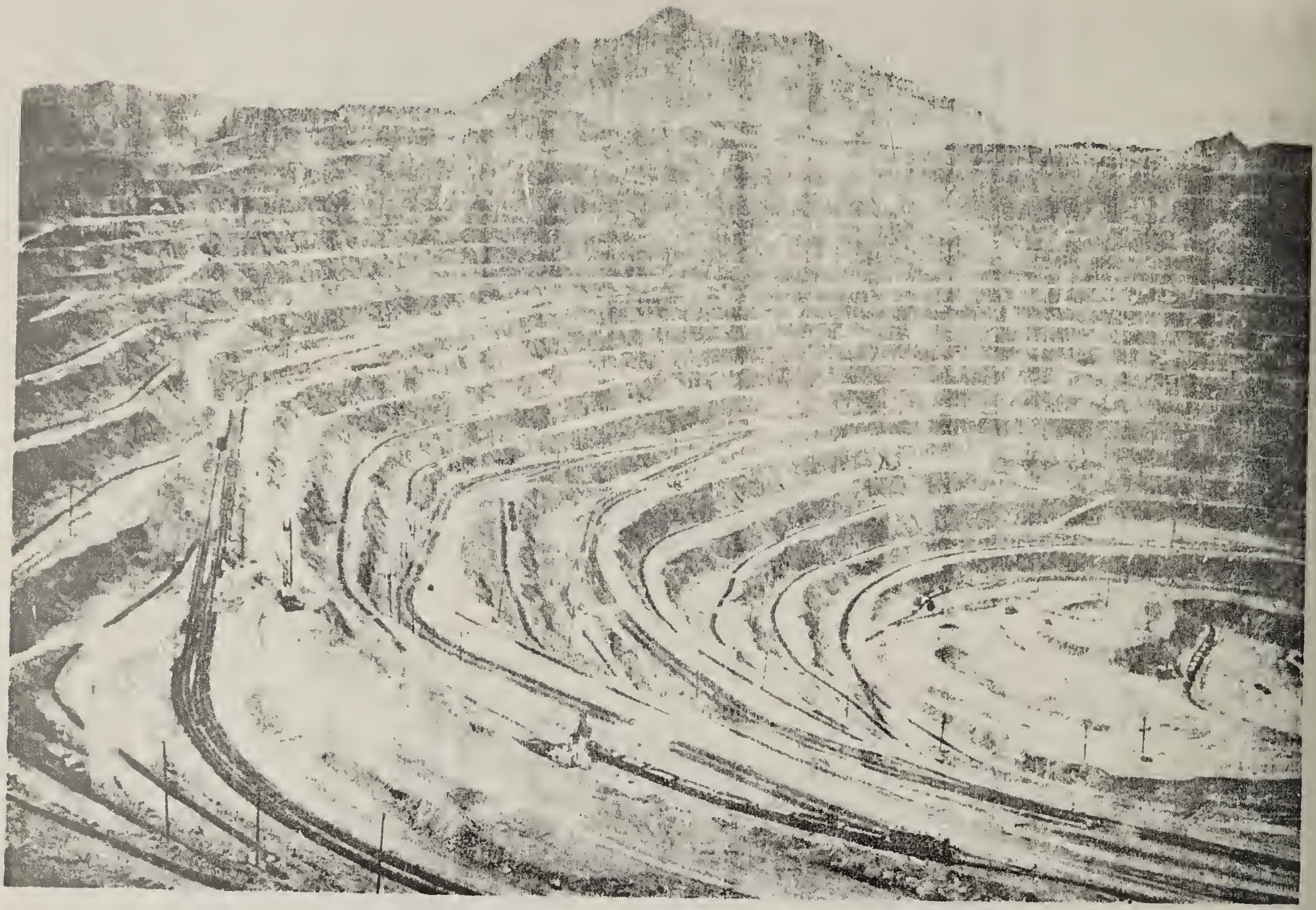


Fig. 76 - The New Cornelia Mine of the Phelps Dodge Corporation at Ajo, Arizona. One of the few large surface mines using rail haulage, it is also one of the most symmetrical of the nation's open pit mines. Even here truck haulage is used in some parts of the mine, primarily in hauling waste from the upper levels.

4. Mining by Leaching

Despite the dominance of traditional underground and open pit methods and the virtual disappearance of placer mining, there are other mineral production methods of significant importance in the mining of nonfuel minerals in the United States today. Probably the most important of these is *leaching.* Although also applicable to a select group of other minerals, leaching is presently used most in the production of copper. Regardless of the specific minerals being leached, however, many of the techniques and equipment are similar. The particular choice of leaching method depends upon the chemical and physical characteristics of the specific material to be treated. The grade of the ore, the solubility of the minerals sought, the amount of acid-consuming associated gangue material, the size of the operation, and the mode of occurrence of the ore minerals are some of the important factors to be considered.

Only one leaching method should properly be considered a mining method, the others actually being techniques for extracting valuable elements from rock that has already been removed from the earth. This method is *in-place* or *in-situ* leaching, in which the ore is subjected to leaching solutions at the site of its original location in the earth's crust.

In-situ leaching, as it has been practiced to date, is normally done in conjunction with an underground mine in which the mining operation has caused the caving and crushing of large masses of mineralized ground above and around the underground openings. If a mining

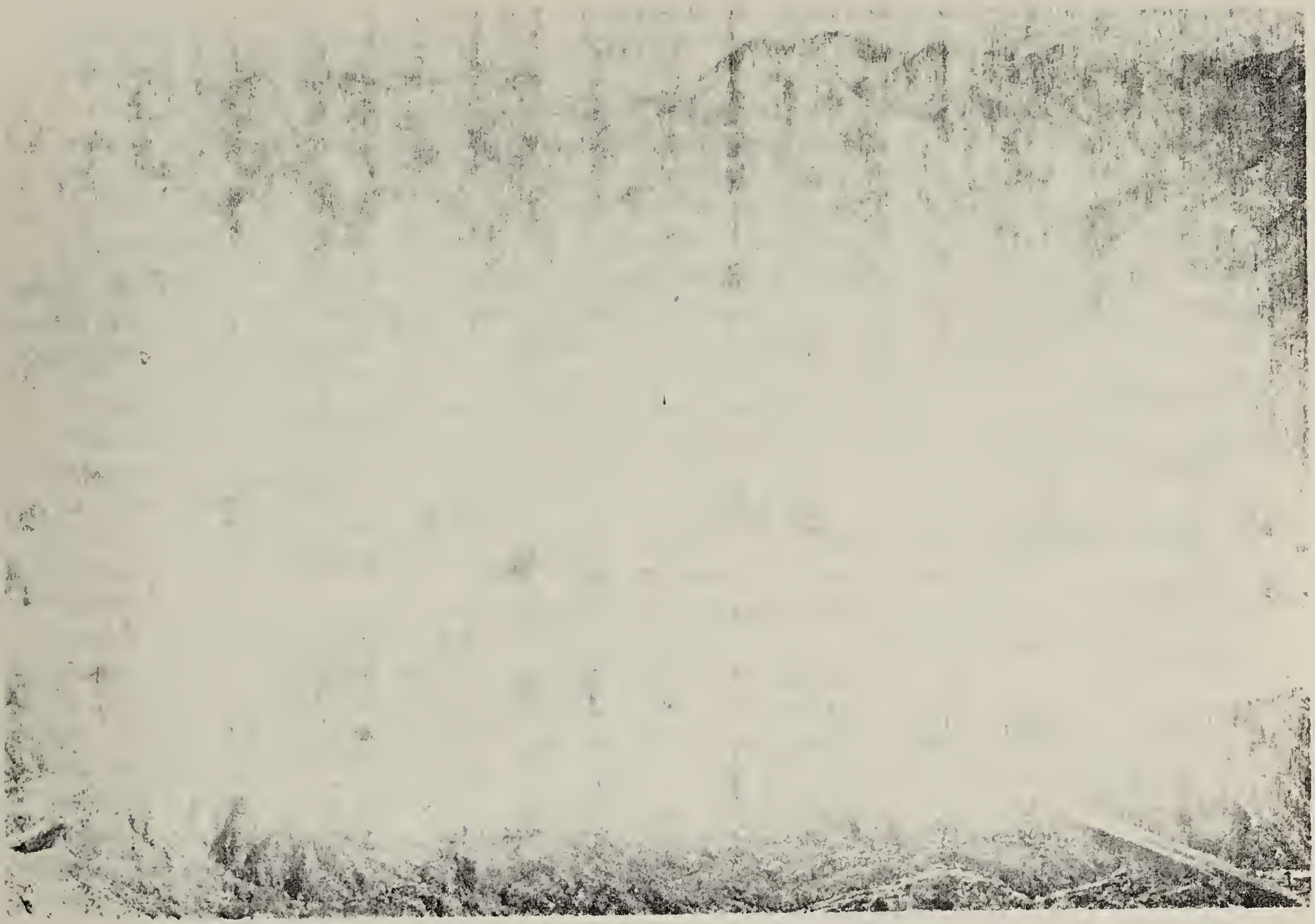


Fig. 77 - The Ray Mine of the Kennecott Copper Corporation at Ray, Arizona. A mine with a highly irregular outline, a portion is located over a former underground operation in an area of irregular terrain and erratic mineralization. Truck haulage is used exclusively in the mine, although crushed ore is later jauled by rail to the beneficiation plant at Hayden, approximately 20 miles away. (Photo courtesy of T.J. McCleneghan)

operation has not been instrumental in crushing the potential leach material, it would then have to be crushed by some other means, such as by contained nuclear blasting. The prior mine openings serve also as a collection reservoir for the leach solutions and as a base of operations for pumping the leach liquors to the surface. Had these subsurface openings not been where they are by virtue of a previous mining operation, part of the required development would be the sinking of a shaft, driving of tunnels, and the cutting of sumps and pumprooms for the leach liquor recovery system.

In-place leaching techniques are applicable to leaching both oxide and sulfide ores of copper and other metals. The basic principles involved are similar to those for other types of leaching. The leach solutions must pass downward through the ore and contact and dissolve the metal-bearing minerals. Adequate arrangements are necessary to collect the resultant metal-bearing liquors without appreciable loss, and provision usually must be made to pump the liquors to the surface where the metallic content can be recovered.

Typical of practice in the copper industry is the operation at Ray, Arizona, where in-place leaching of copper was done on worked-out areas of the Ray Mine. Water sprays were moved from one area of the surface to another to uniformly distribute fresh water to the caved area created by earlier block caving operations. This practice promoted the

Table 34

CEMENT COPPER PRODUCED FROM LEACHING OPERATIONS AT MAJOR COPPER PROPERTIES IN THE WESTERN UNITED STATES, 1964

Mine	Cement Copper (tons)	Copper Sulfide Concentrates (tons)	Total (tons)	Proportion of Cement Copper (percent)
MORENCI	800	128,600	129,400	0.6
COPPER QUEEN	5,400	58,200	63,600	8.5
NEW CORNELIA	–	70,689	60,689	–
MIAMI	13,000	19,000	32,000	41
RAY	9,040	50,200	59,240	15
CHINO	27,421	56,388	83,809	33
INSPIRATION	3,807	19,697	23,504	16
SAN MANUEL	–	94,895	94,895	–
BAGDAD	7,753	11,878	19,631	40
SILVER BELL	2,400	21,200	23,600	10
MISSION	--	52,400	52,400	–
PIMA	–	30,000	30,000	–
ESPERANZA	2,000	19,000	21,000	10
MINERAL PARK	--	19,000	19,000	--

Source of data: *Mining Engineering,* October 1965.

oxidation of both iron pyrite and the remaining copper minerals and therefore their dissolution. The copper-bearing liquors were pumped to the surface, and the copper was recovered by precipitation with iron.

The Miami mine of the Miami Copper Company is probably the best example of a current in-situ leaching operation. The company is leaching copper from the remains of the underground orebodies which previously were mined principally by block caving methods. Various small amounts of copper remain in the waste capping, in the stopes below the capping, and in the crushed pillars in the mine. At Miami, acid is added to tailing water from the precipitation plant, and this solution is distributed by sprays onto the surface area which overlies the former block caving operation. The leach solution percolates downward through 600 feet of material, the bottom 150 feet of which contains the mixture of ore and waste with the highest percentage of copper. The solution moves from the surface to the 1,000-foot level of the mine within three to four weeks. Pregnant liquor that is collected in a reservoir on the 1,000-foot level is emptied periodically into a sump from which the liquor is pumped to the precipitation plant on the surface.

Most other mines in the copper industry employ one or more of the other types of leaching. At Ray, both in-place and dump leaching have been practiced. *Dump leaching* is typically used for low-grade and waste material stripped from open pit operations. Run-of-mine ore materials containing metal in amounts less than the existing cutoff grade (usually 0.4 percent for copper) deemed necessary for the profitable recovery by the usual mining and concentrating methods are leached by this method.

Most leach dumps are deposited upon existing topography. The locations of the dumps are selected to assure impermeable basement surfaces and to utilize the natural slope of ridges and valleys for the recovery and collection of the pregnant liquors. Examples of this method of dump emplacement are found at numerous copper leaching operations in Arizona, Nevada, New Mexico, and Utah. In several instances, leach dumps have been deposited on specially prepared areas. Ground preparation for dump emplacement varies from property to property, but there are a number of basic similarities.

The original surface under the dump areas of the Anaconda Company at Butte, Montana, is composed of from five to 80 feet of alluvium which has been deposited naturally on top of quartz monzonite bedrock. Because solution loss through the alluvial material would have been substantial, an impervious pad to prevent solution loss was constructed in steps. First, the vegetation was removed by bulldozers, and then the scraped surface was graded and compacted using sheepsfoot and vibratory rollers. Second, a four-inch layer of crushed slag was placed on the surface and compacted with a vibratory roller. This was followed by a coating of asphalt primer placed above the slag, and then by a compacted layer of asphalt (blacktop) placed on top of the primed surface of the slag. Next, a thin layer of asphaltic sealant was blown onto the surface of the blacktop. Over this, a one-foot minimum thickness of fine pit-run material was placed on the asphalt mat to protect the surface from rupture by heavy truck traffic. Finally, a five- to six-foot thickness of coarse pit-run material was placed on top of the fine material to provide protection against damage of the pad by boulders cascading down the slope of the high dump. All of this was before any leach material was placed on the dump. To date, the recovery of leaching solutions from the dumps constructed on this impervious pad has been very high.[129]

In another situation, with a different original surface, the leach dumps at the Weed Heights, Nevada, operation of the same company were placed on a dry lakebed after the lakebed had been graded by bulldozers and compacted by sheepsfoot rollers. Dumps in other locales have been constructed on various types of bedrock or have required similar processes to construct an impervious surface on otherwise permeable material. In a few places, waste dumps have been situated over old underground workings and so have worked in conjunction with in-situ leaching and have not required an impermeable base.

Leach material, in most operations, is hauled from open pit mines to dumps by trucks or trains. Bulldozers are then used to level the surfaces and edges of the dumps. Large waste or

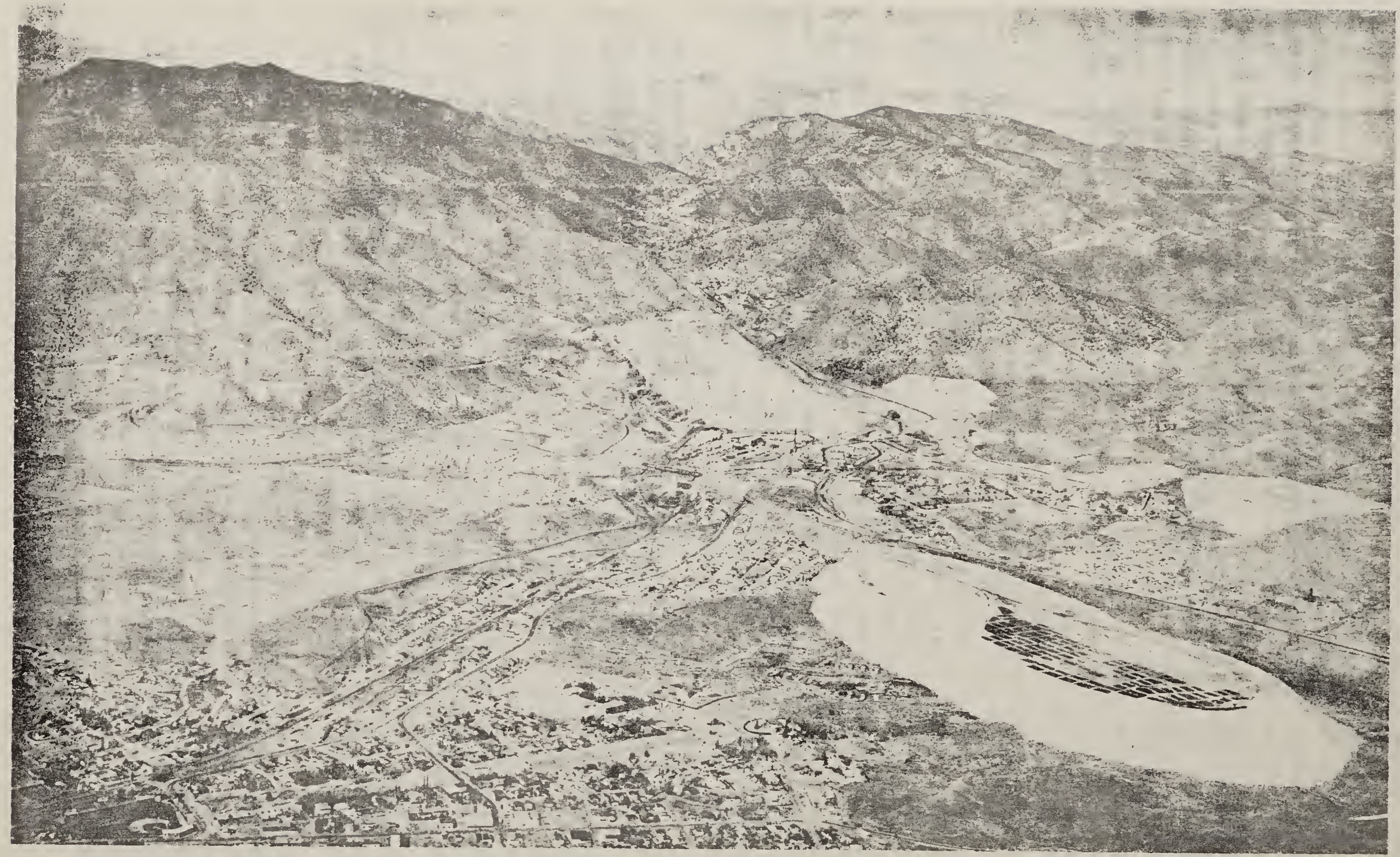


Fig. 78 - Aerial view of the leach dump of the Phelps Dodge Corporation at Bisbee, Arizona, in 1960, looking generally north. The Lavender Pit from which the leach material has been removed is in the upper center of the picture. The underground Copper Queen Mine, an underground operation in higher-grade replacement deposits in limestone, extends generally south and west of the pit. The waste dump, with leach ponds covering more than half of its surface, extends southeastward from the mine.

leaching dumps usually are raised in lifts of from 50 to 100 feet in a manner designed to keep haulage costs minimal with respect to both the grade of ascent required and the maximum distance of haul, as well as to form a porous dump favorable for the percolation of leach solutions.

The majority of the material currently placed on leach dumps is run-of-mine material that has been loaded by power shovels as part of the surface normal mining operation. The leach material therefore includes boulders as large as several feet in diameter and weighing many tons, but most of the material is less than two feet in diameter and includes many fine particles. Leach material being placed on dumps at present is generally smaller in size than that placed on dumps in the past. The reduction in size is chiefly the result of improved blasting techniques which provide better rock fragmentation.

The shape of most leach dumps is that of a truncated cone. This configuration is developed by the method of dump emplacement used in most operations. The leach material forms a slope having an angle of repose peculiar to the type and size of material. The tonnage of the major copper leach dumps in the Western United States varies approximately from less than six million tons at the Mineral Park, Arizona, operations of the Duval Corporation, to four billion tons at the Bingham Canyon, Utah, operation of Kennecott Copper Corporation.[130]

Most leach dumps settle after the leach solutions have been introduced because the percolating solutions tend to transport the finer particles into the voids between the larger particles (and thereby compact the dump as a whole) and because the total weight of the dump is increased by the weight of the solutions which causes a downward compression of the dump. The disintegration and dissolution of minerals in the dump, of course, also cause the dump to settle. Active dumps, therefore, are usually in movement and not stable.

The leaching operation comprises the introduction of an acid solution onto the surface or into the interior of the dumps for the purpose of effecting the dissolution of contained minerals. The end product of the copper leaching operation is a pregnant liquor containing copper in the form of copper sulfate. Most companies recirculate the tailing solutions from their precipitation operations, along with additional makeup water and concentrated sulfuric acid as the leach solution. Makeup water is added to replenish the water lost by evaporation or seepage during leaching. Sulfuric acid is added to lower the pH of the leach solution generally to assure adequate acidity for dissolution of the copper minerals, but at the same time to prevent the destruction of bacteria in the dumps, and also to minimize the hydrolyzation and precipitation of iron and other metals in pipelines, on the surface, or in the interior of the dumps.

Water added to the leach solution normally comes from several sources, including wells, springs, underground mines, or nearby streams. Polluted stream waters from nearby towns are sometimes used, but the organic material contained in sewage waters is considered to be a deterrent to bacterial activity within the leach dump and therefore is not used in many leach circuits. Leaching operations require water that is less contaminated with organic matter than the waste effluent from most urban areas.

The sulfuric acid used in most of the larger leaching operations is produced and supplied by the operating company itself. In smaller operations the acid is obtained from commercial suppliers. The development of contact sulfuric acid plants coupled with a constant supply of high-grade sulfur has simplified the manufacture of sulfuric acid, and many copper producers now make their own leaching acid.

Leach solutions are introduced onto or into dumps by means of spraying or flooding, or through vertical pipes. The method chosen for a given operation is based on careful consideration and knowledge of climatic conditions, dump height, surface area, mineralogy, scale of operation, and size of leach material. Leach solutions at several operations are introduced onto the dumps by various methods of spraying. The main advantage of spraying is that it provides a uniform distribution of the leach solutions over the surface area of the dumps, but the evaporation loss in arid regions may range up to 60 percent. The commonest spraying method involves the use of perforated plastic pipes. The Inspiration Consolidated

Copper Company at Inspiration, Arizona, and the Anaconda Company at Weed Heights, Nevada, both use this method. The solution is pumped to the top of the dump through cement-asbestos, plastic-lined pipes and is carried from the main distributing lines in smaller, perforated plastic pipes. The pressure created in the pipelines causes the leach solution to be discharged through the perforations in the form of a spray. The height and distance of coverage of the sprays are, of course, functions of the pipeline pressures.

Spraying methods also are used to distribute leach solutions over the slope portions of dumps, the tops of which are being leached by flooding methods. In such spraying, lengths of small-diameter plastic pipes are placed on the slope area from the top to the base of the dumps. Proper coverage of the slope area is extremely difficult because the solutions tend to form channels down the slope and flow rapidly from the slopes without penetrating the surface. Large tonnages of material on the slope face, therefore, are not usually contacted by the leach solutions.

At some properties, leach solutions are introduced onto the dumps by flooding or ponding, i.e., by forming furrows, ditches, ponds, or channels on the dump surface by bull-dozers or front-end loaders. The leach solutions are channeled into these conduits and allowed to build up to a certain depth in order to create a substantial flow of solution onto the dumps. In actual practice, a section of a dump is flooded with leach solution until such time as the copper content of the pregnant liquor obtained from the section falls below a predetermined percentage. The flooding then is discontinued on that section and begun on another. Alternating periods of wetting and drying of leach dumps apparently produces the most efficient dissolution and removal of copper from the leach material.

Probably the newest method of solution introduction is that practiced at the Butte, Montana, operation of the Anaconda Company. The leach solution is introduced through perforated plastic pipes into the interior of the dumps. Six-inch churn-drill holes are drilled at the intersections of a 100-foot grid pattern and cased to a depth of about two-thirds the dump height. A four-inch perforated plastic pipe is then placed inside the casing over the entire depth of each hole, and the casing is removed. Leach solution flows to the dump area from solution reservoirs at a higher elevation. Ditches are provided along the drilling grid lines to permit the solution to flow into the top of the plastic pipes and down the drillholes. The method promotes a greater distribution of air and leach solution within the dumps. The slope areas of the high dump at the Butte operation are also wetted with leach solution through cased churn-drill holes that have been drilled on side-slope roads constructed by bulldozers. The entire operation might almost be termed a type of secondary solution mining.

Closely akin to dump leaching is *heap leaching*. This method is used to dissolve metallic minerals from porous oxide ores that have been placed on a prepared surface. Heap leaching contrasts with dump leaching principally in that *ore* material is leached rather than *waste* material. This method is not readily applicable to the dissolution of high concentrations of copper sulfide minerals or to ores containing large amounts of carbonates or other acid soluble gangue minerals. It is in fact, as well as in effect, a beneficiation method rather than a mining method.

Even more an advanced processing method than a beneficiation method is *vat leaching*. This method is used in preference to heap leaching if the ore material is not porous and crushing is necessary to permit adequate contact between the leach solution and the minerals to be dissolved. Despite the increased costs necessary for crushing and screening, numerous advantages are obtained by vat leaching in copper production. Higher copper recovery in shorter periods (than in heap leaching) is realized. Pregnant liquor losses are negligible, and the copper content of the pregnant liquor is usually much higher, permitting the recovery of the dissolved copper by means other than precipitation by iron.

In the United States today, copper is recovered from leach liquors almost entirely by means of precipitation by scrap iron. Copper in the vat leach liquors at the Inspiration Consolidated Copper Company plant in Arizona is recovered by electrolytic deposition. Other methods of precipitation have been suggested and tried, and more are being developed.

5. Solution Mining

Closely related to the leaching of disturbed metal-bearing rock as a mining method is the technique known as solution mining. In solution mining methods, water is injected into subterranean salt deposits, forming an artificial brine which is pumped to the surface, where the salt content is removed and utilized. About two-thirds of domestic salt (sodium chloride) output is produced by introducing water into a cavity in the salt deposits and removing the brine. This procedure is relatively simple and has particular advantage when the salt is to be used as a brine, as in chemical uses such as soda ash and caustic manufacture.

In the solution mining of sodium chloride, holes are drilled through the overburden into the deposit and cased with iron pipe. Water is introduced into the deposit through a smaller pipe inside the casing. A nearly saturated brine is formed in the cavity at the foot of the pipe. This brine is pumped or airlifted through the annular space between the two pipes.

Numerous techniques have been developed to control the shape of the cavity so that a saturated brine will be formed and so that the eventual subsidence and caving of the cavity will result in the least damage to the well. Most of these techniques involve positioning of the water intake and brine exit pipes in the cavity and the employment of a cushion of air to control the degree of contact between the solvent and the salt formation. After adjacent wells have been operated one or two years, their cavities may become connected. When this occurs, the usual practice is to introduce water into one well and remove brine from the other.

In recent years, hydraulic fracturing techniques have been used to form channels between wells. First developed by oil producers to increase petroleum output, these techniques were adapted with great success to the solution mining of salt and resulted in increased efficiency. With this technique, a series of wells is drilled to the base of a salt formation. The wells are made to interconnect by injecting water under high pressure into one of the wells and continuing to pump water into the ground until a fracture occurs to a nearby well or wells. In the mining operation, fresh water is introduced into one well and saturated brine is removed from the others.

The cavities developed in salt mines both by dry mining and solution mining techniques have been found to be admirably adapted as storage vaults. Rock salt normally has strength enough to support itself over moderate spans without danger of collapse. Salt formations have good thermal conductivity and are relatively impervious to seepages of water, so that the cavities formed by mining have an even temperature and relatively low humidity. The principal rock-salt areas in the United States have a good record of earthquake stability and, therefore, the storage of petroleum products and radioactive wastes in salt cavities is said to be economical and safe. Furthermore, many of the physical and chemical properties of salt beds are well adapted to the storage of hot chemical materials in liquid form.[131]

Solution mining has also been applied to potassium minerals and other soluble salts occurring in deposits too deep for surface operations. In some cases the minerals are already in brine form and mining simply consists of tapping the brine formation and removing the mineral-bearing water. To date, the method has been restricted mostly to non-metallics that are highly soluble, but proposed nuclear blasting followed by in-situ leaching may expand the method to base metals as well. Some work has already been done in the solution mining of uranium. While still largely in the experimental stage, solution mining has been demonstrated to be a workable production method for uranium when applied under proper conditions. Where it has been mined successfully by solution methods, the uranium ore occurred in a generally horizontal bed underlain by a relatively impermeable stratum. In addition, the uranium ore occurred below the static water table, and the direction and volume of regional water flow were known. Where the solution mining of uranium has been successful, the mineral content of the area was more than sufficient to repay the costs of the entire operation. Solution mining has not been an inexpensive process and should not be considered as a scavenging operation.[132]

In the solution mining of uranium that is under development in the Shirley Basin in Wyoming, the well pattern consists of three inflow wells located about 25 feet upstream from a centrally located production well. Stainless steel screens are placed in the wells at the ore formation and cemented off and cased to isolate the ore from other horizons. The wells are developed by high-pressure jets to take a satisfactory rate of flow. Leaching is started by injecting the three upstream inflow wells with sulfuric acid at the same time that pumping is started in the downstream production well. A given area may require from one to several months of pumping, depending largely on the amount of uranium present and the rate of pumping that is possible. Recoveries are difficult to estimate, with little experience to date, but indications are that overall recoveries will equal or exceed that of underground mining.

Costs from this method have been found to be lower than those which had been previously experienced in underground mining operations in the same district. Furthermore, a lower capital investment is required than with ordinary underground mining. Another advantage is increased safety, inasmuch as many of the usual hazards (including radiation exposure in uranium mining) involved in excavation, either on surface or underground, are eliminated.

6. Frasch Process Sulfur Mining

Another method of mining that is similar in many respects to solution mining is the Frasch process used in sulfur mining. Almost all of the native sulfur now being produced in the United States is mined by the Frasch hot-water process from salt dome sulfur deposits. Only very small quantities are mined by open pit from near-surface deposits.

The idea behind the Frasch process is extremely simple. Very hot water under pressure pumped through a drill hole from the surface can melt sulfur in place so that it will flow and can be carried to the surface by compressed air. In practice, the process is more difficult and has been applied successfully to only a few deposits. Of the 230 or more salt domes known in Louisiana and Texas, only 22 have been producers of sulfur. Of these, ten were active in the mid-1960's. To be mineable by the Frasch process, the sulfur-bearing formation must have some porosity to permit entrance of hot water, but the enclosing structure must be impermeable enough to restrict the molten sulfur and water from being lost to the surrounding ground.

In the development of a Frasch process mine, wells are drilled through the sulfur zone to barren anhydrite below. Mining depths in the United States have ranged from 400 to 3,000 feet. The wells are drilled with a rotary rig, similar to those used in the petroleum industry, and are equipped with concentric pipes ranging in size from one to eight inches in diameter. A typical installation may have a six-inch pipe to the barren anhydrite. This pipe has two sets of holes near the bottom which are separated by an internal collar. A three-inch pipe placed inside the six-inch pipe rests on the collar near the bottom of the sulfur formation. The collar seals the annular space between two pipes. The one-inch pipe inside the three-inch pipe reaches nearly to the collar.

The water to be injected into the sulfur-bearing formation is heated to 325 degrees to 340 degrees F at the plant, but this is reduced to 320 degrees to 325 degrees F in the field. Control of water temperature is important because, although the water should be as hot as possible for heat transfer reasons, above 318 degrees F the viscosity of sulfur increases suddenly, causing sulfur removal problems. The volume of water used per ton of sulfur recovered ranges from less than 1,500 gallons per ton in a highly efficient mine to 1,500 to 3,000 gallons per ton in many mines now in operation. It may run as high as 7,000 gallons per ton in a lean, less favorable deposit.

The pumps used in the Frasch process may supply water at 250 to 350 pounds per square inch pressure, but water under 125 to 200 pounds per square inch pressure is normally used at the wells. The depth of the well, the length of the surface line, the porosity of the sulfur-bearing formation, and the volume of water used are all related to the pressure needed. The hot water under pressure is transported to the ore horizon between the six-inch and three-inch pipes and enters th fur formation through the upper set of holes above the collar. The liquid sulfur, bein avier than water, settles to the bottom around the six-inch pipe. Liquid sulfur enters t pipe through the lower set of holes below the collar and is forced into the space betw n the three-inch and one-inch pipes by hydrostatic pressure. Compressed air entering th liquid sulfur through the one-inch pipe decreases the density, and the column of fluid sulfur rises to the surface. Bleeder wells are used to remove cool water in order to make room for the hot water being piped into the dome.

Air compressors delivering pressures of 500 to 600 pounds per square inch are used in the Frasch process. The depth of the well, the length of air line, and the pumping rate cause pressure variations from one well to another. It normally requires from 500 to 900 cubic feet of air to mine a long ton of sulfur.

Liquid sulfur reaching the surface is discharged into steam-heated tanks at relay stations. The same relay stations also conduct the flow of air and water to the wells. After being metered, the sulfur is pumped through steam-heated lines either to storage vats, where it cools and solidifies, or to liquid storage tanks. Shipments of either solid or liquid can be made by rail, road, inland waterways, or ocean. Approximately 85 percent of the deliveries of sulfur to domestic markets in the mid-1960's were in liquid form.

The removal of large quantities of sulfur from a given deposit may have several effects. The formation of voids and cavities in the rock may increase the water-to-sulfur ratio and thereby increase the cost of production. In addition, subsidence may distort or break the pipe in the wells and disturb surface installations in the immediate area. These effects can be partially offset. In order to reduce hot water requirements, the voids and crevices are sometimes filled with special mud. Subsidence resulting from the removal of large amounts of sulfur can be advantageous in that it fills voids, thereby eliminating the necessity for filling them with mud.[133]

7. Beneficiation Practice

At the present time virtually all nonfuel minerals beneficiation in the United States involves some type of *crushing* in which lumps of material from the mine are first crushed by primary gyratory or jaw crushers. Intermediate crushers, either cone or roll crushers, are used to further reduce the ore particles to approximately one-fourth inch to three-fourth inch in size. Crushing is normally followed by *grinding* where some type of concentration is to be performed. Fine grinding is most frequently done in a modified cylindrical mill rotating on a horizontal axis and containing steel balls, rods, or ceramic pebbles as a grinding medium. Depending on the grinding medium used, these are called ball mills, rod mills, or pebble mills.

In order to size the crushed and ground particles, two methods are now commonly used. Crushed material is usually passed through screens for sizing in an essentially dry process, while ground material is usually passed through classifiers, an essentially wet process. Drag and spiral classifiers have been displaced by cyclone classifiers in many of the newer or remodeled mills. Cyclones are small, relatively simple machines with no moving parts, and they require only a fraction of the floor space needed for conventional classifiers of equivalent capacity. Since they are based on the action of centrifugal force rather than gravity, however, they require more power.

Despite the prevalence of froth flotation, gravity *concentration* methods effecting a mineral separation by virtue of differences in mineral densities are still widely employed. Current methods used to upgrade various ores are jigging, heavy-media separation, tabling, and spiral separation. Jigging depends upon the differences in settling rates of minerals in water as they are carried over and through a screen bed subjected to a vertical pulsating action. Heavy-media methods are based on the principle that solid particles will float in a fluid medium if the medium has a higher density, but particles with a greater density than the medium will sink. In practice, the media used are commonly thick pulps of finely ground material such as ferrosilicon, magnetite, galena, or sand suspended in water.

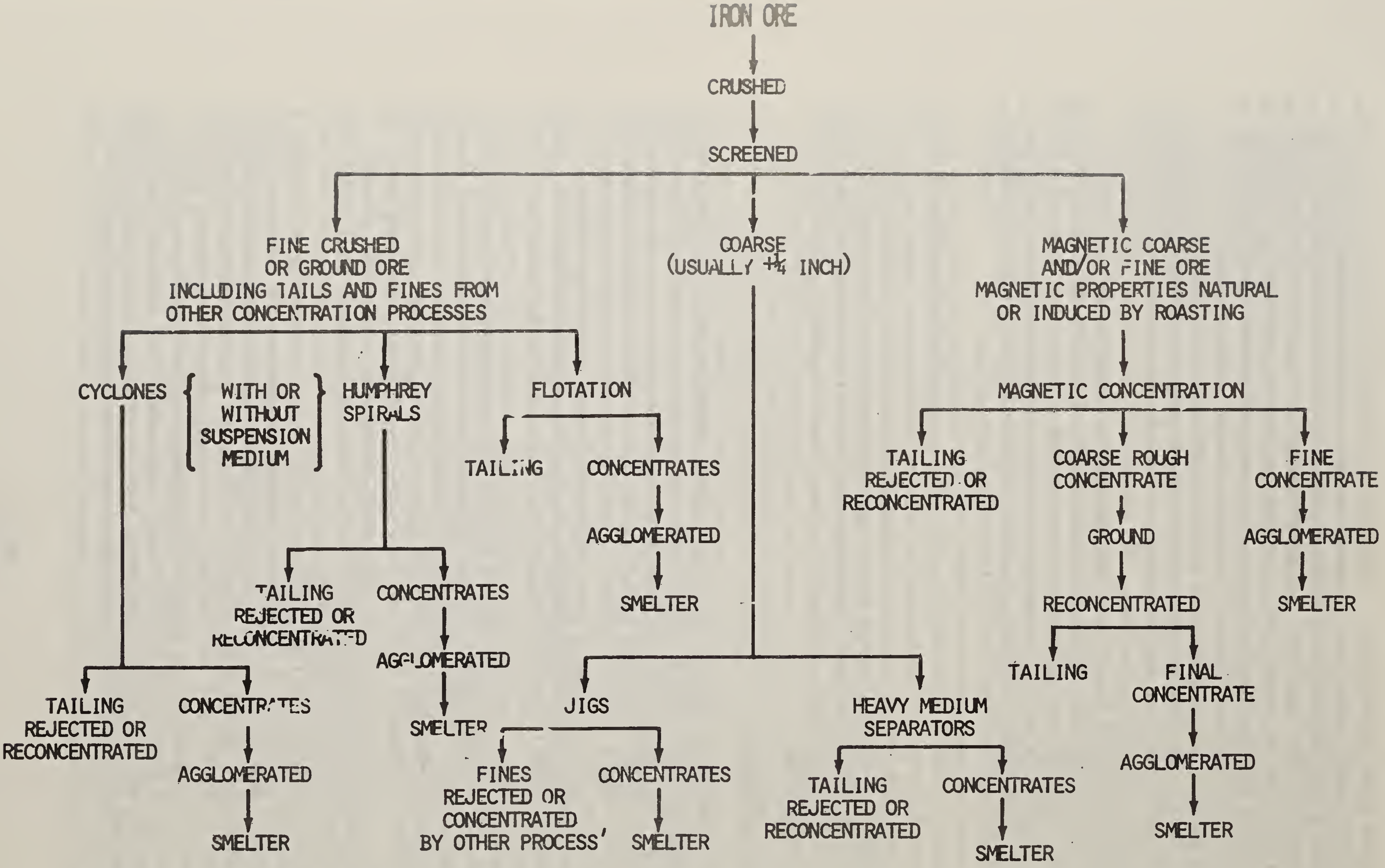


Fig. 79 - Beneficiation of iron ores mined in the United States today is far more complex than in previous decades. Lower-grade ores and different metallurgical processes have made new demands on beneficiation technology and equipment and on the space required for them.

Jigging and heavy-media minera[illegible]aration methods are applicable to material that has been crushed to 48 mesh (0.012 in[illegible]ameter) or larger. In present practice, the maximum particle size is about three inches [illegible]onsiderable gravity differences must exist between minerals for effective separation at [illegible] mesh, and coarser feed is therefore necessary for ore in which the various minerals have [illegible]all density differentials. Mineral sizing is thus very important for effective separation using jigs, although heavy-media methods require no preliminary sizing except for the removal of untreatable undersize. Jigging is effective if the minerals to be separated have a specific gravity difference of 0.5 or more, although closely sized fractions of feed treated on separate jigs may have a gravity differential of as little as 0.25. Heavy-media methods can make an effective separation between particles having a specific gravity of about 3.5 or less (usually gangue minerals) and those that are heavier (usually ore minerals).

Tabling is applicable to ore having fine particle sizes. The optimum size of material for this method of gravity concentration ranges from ten mesh (0.065 inch in diameter) to 100 mesh (0.0058 inch in diameter). A specific gravity difference between minerals to be separated is usually at least 0.5, but departures from both specific gravity differentials and size range are sometimes effectively tolerated if the feed size is classified between narrow limits. Tabling now occupies a minor role in the scheme of mineral dressing for metalliferous ores because the froth flotation process is generally more efficient in treating particle sizes smaller than 35 mesh (0.016 inch in diameter). Nevertheless, tabling is still useful for concentrating tungsten minerals and the heavy minerals found in beach sand deposits.

The Humphreys spiral is a flowing-film type of gravity concentrator now used extensively in iron ore beneficiation. It consists of a trough which is wound into a spiral and stands in a vertical position. Concentration is made on a dilute ore-water mixture which is fed into the top of the trough and allowed to spin down through it. The heavier minerals settle quickly to the bottom of the trough, while the lighter mineral particles tend to ride up on the outer side of the spiral. The lighter minerals are discharged at the lower end of the trough, while the heavier minerals are collected in ports along the inner side of the spiral.[134] Many ores today contain finely disseminated metalliferous minerals and require fine grinding to secure their liberation. Fine particles have large surface areas relative to their mass and their surface energy characteristics therefore dominate their mass characteristics so that the particles respond poorly to gravity. For these reasons, *froth flotation* has become the most commonly used concentration method for nonferrous metal-bearing ores.

Froth flotation is a concentration technique in which finely ground mineral surfaces are treated to effect their wettability. Mineral particles whose surfaces have been made non-wettable are held at the water surface by surface tension forces while those minerals with wettable surfaces do not tend to float. Since flotation is dependent upon different surface characteristics, several groups of chemical reagents are required to effect mineral separation. Reagents are divided into collectors, frothers, depressors, activators, and collectors. Collectors are chemical reagents which react with the surface of a mineral particle to produce an air-greedy surface. Frothers are added to the fluid pulp to prevent the mineral-coated air bubbles from breaking prematurely. Depressors are often added to the pulp to react with the surfaces of minerals to prevent their flotation. Activators react with the mineral surfaces to make the collectors more reactive in adhering to selected mineral particles. Conditioners are chemicals added to flotation pulps to regulate their acidity or alkalinity.

Magnetic concentration methods depend upon the differences in magnetic properties of minerals to effect their separation. Magnetite is the predominant iron-bearing mineral concentrated by these methods, because it is naturally attracted to a magnet. Other non-magnetic iron-bearing minerals are sometimes heated in a roaster to induce magnetic properties which make them amenable to magnetic separation.

Electrostatic separation of minerals is based on the principle that like charges repel and unlike charges attract. In this concentration method, small particles of dry ore are charged as they fall through a field of high-voltage direct current electricity of between 18,000 and 80,000 volts. Conducting minerals become polarized and lose their electrons easily, and thus

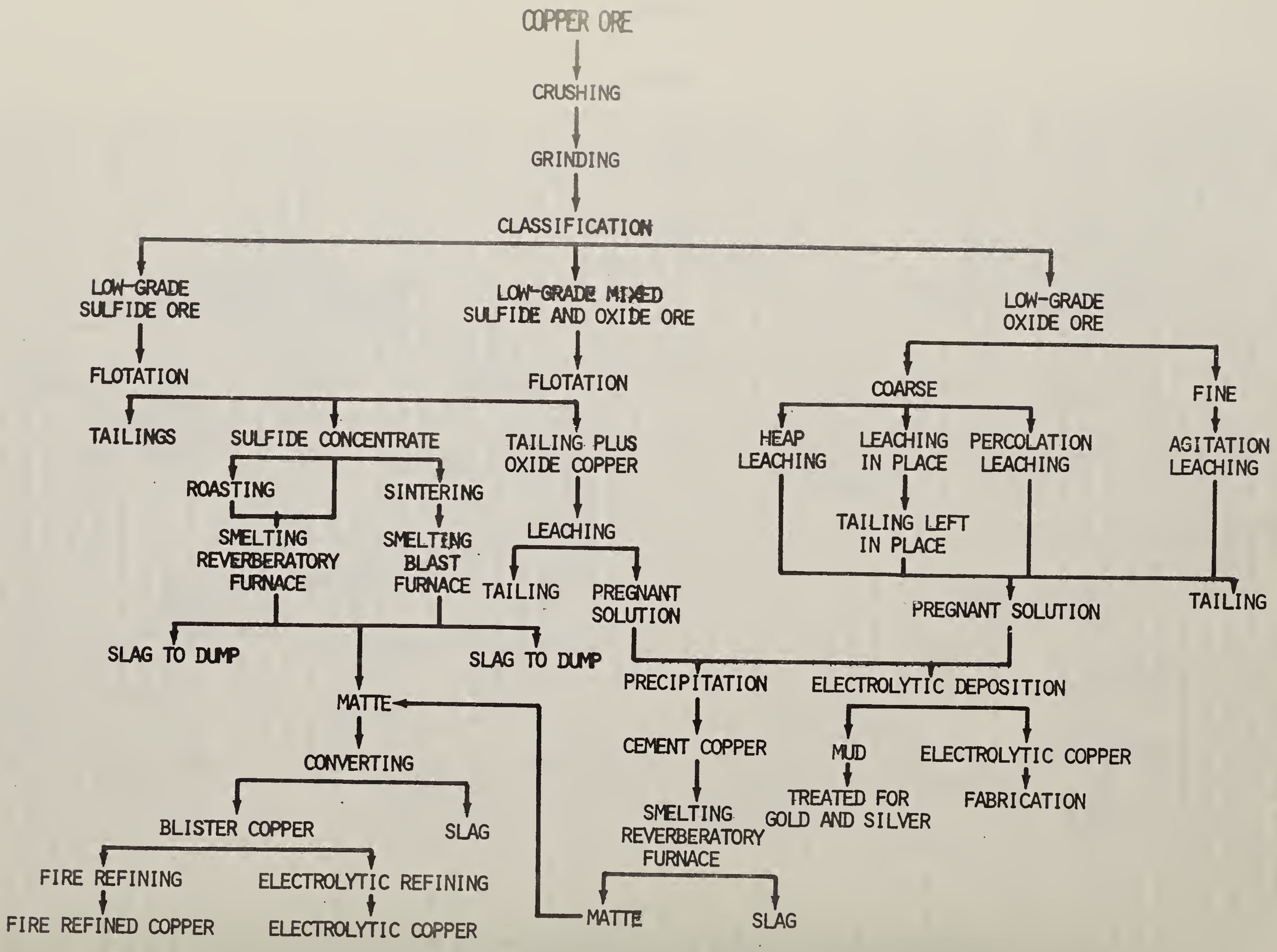


Fig. 80- The beneficiation and advanced processing of copper ore today involves more alternatives than at any previous time, and various methods and processes may be used on minerals from the same deposit.

become positively charged, and th ore are repelled by the positive side of the field. Insulating or dielectric minerals bec polarized, but do not lose electrons, and therefore are attracted to the positive side of field. Semi-conducting minerals become polarized, but lose their electrons at a slowe ate than conducting minerals, and eventually are repelled by the positive side of the eld. Such methods are often used in gaseous waste control as well as in beneficiation.

In the beneficiation of industrial minerals, many of the methods and equipment used are similar to those used in treating metallic ores. In treating industrial minerals, as in metalliferous minerals, only materials with high unit values can economically survive expensive processing. As a result, many commodities are subjected only to simple sizing and cleaning operations while others may undergo long and complex procedures in which beneficiation and more advanced processing operations are combined.

Asbestos is actually a commercial term applied to several naturally fibrous minerals including chrysotile, crocidolite, amosite, anthopyllite, tremolite, and actinolite. These minerals have different chemical and physical properties. Virtually all of the asbestos production in the United States and about 95 percent of the world supply is chrysotile asbestos. Chrysotile is marketed as either crude or milled fiber, and crude is defined as hand-cobbed vein material essentially in its native or rock-like form.

The beneficiation methods used with chrysotile asbestos generally consist of repetitive crushing and screening and the removal of the freed fiber after each stage by air suction hoods. In this manner, the chrysotile fibers are teased out of the rock with a minimum of abrasion and cutting of the fibers. In milling chrysotile, the long fibers are conserved by every possible means, because they are the most valuable. For example, Group Number 3 grade of asbestos, which is a milled spinning fiber, sold in 1965 for prices ranging between $345.00 and $750.00 per ton. The higher price was paid for fibers without iron impurities. In comparison, the price for Group Number 7 fibers was between $40.00 and $90.00 per ton. Group Number 7 includes milled short or refuse fiber. Special milling techniques have been developed for matted short-fiber chrysotile which includes wet grinding and filtering, with the filtering used to collect the fiber which has been suspended in water.

Asbestos is delivered to the user as crude, unopened fibers, as half-opened fibers, and as fully opened mill fibers. In any event the fibers must be separated or opened before they can be used. Opening the fibers in some cases also separates adhering or inclosed gangue minerals. Therefore, the advanced processes which asbestos must undergo before it is made into a useful product are opening and cleaning. These are done in a variety of specialized machines, all designed to meet the market requirements for the finished product within the constraints imposed by the nature of the raw material. Other minerals used in construction are treated similarly.

A large quantity of high-grade gypsum is and has been available in the United States at a relatively low price. In the mid-1960's, the average price for crude gypsum was about $4.00 per ton, and under the circumstances little attempt has been made to beneficiate low-grade gypsum. Nearly 30 percent of the gypsum produced in the United States is used as uncalcined gypsum, and uncalcined gypsum requires only crushing and grinding, followed only by screening and classification.

Gypsum is generally crushed in two stages. In the first stage, jaw or gyratory crushers are used to reduce the crude ore to minus three-inch size. In the second stage, hammer mills or roll crushers reduce the ore to half-inch size, which is suitable for the rotary calcining kiln or the fine grinding circuit. Various types of pulverizing equipment including tube mills, hammer mills, and rolls are used for fine grinding gypsum. Grinding may take place before or after calcination, depending upon the calcination process used.

In a few localities, gypsum is upgraded with heavy-media separation equipment. Flotation methods have also been used to free gypsum from silica if silica-free gypsum is required for special glass or ceramic use.

Limestone undergoes both beneficiation and advanced treatment processes similar to gypsum, depending of course on whether the end product is for cement manufacture, agricultural or chemical lime, metallurgical flux, direct use in construction, or one of the other uses of limestone, and also depending upon the physical and chemical characteristics of the raw limestone. For direct construction and some agricultural and metallurgical uses, the run-of-mine limestone is simply sized and cleaned. In producing lime and cement, the crude rock must also be calcined, i.e., heated to drive off water and carbon dioxide.

8. Advanced Processing of Industrial Minerals

The treatment of many industrial minerals destined for use as chemical raw materials combines both beneficiation and advanced processing. Such minerals include phosphate, potash, and the various sodium compounds.

Some of the phosphate rock produced in the United States is of suitable grade as it comes from the mine, but a great deal of domestic phosphate rock must be treated by washing, flotation, and other methods. Washing is accomplished by using log washers, screens, various types of classifiers, and mills to disintegrate clay and other fine materials. Fine granular material is treated in flotation cells, spirals, cyclones, cones, or tables. Concentrated phosphate rock is then dried and marketed or sent to advanced processes for chemical treatment.

Potassium compounds are recovered in the United States as solids from salt beds and from brines. About 90 percent of domestic production comes from the large salt beds of Southeastern New Mexico. The potassium-bearing minerals of current economic value are *carnalite, kainite langbeinite, niter,* and *sylvite.* The major ore from the underground mines in New Mexico, however, is *sylvinite,* which is a mixture of *sylvite* (potassium chloride) and *halite* (sodium chloride).[135]

Two basic methods of ore treatment, flotation and fractional crystallization, are used in the Carlsbad, New Mexico, area to recover the sylvite from the ore. The sylvite is separated from the halite in a brine that has been saturated with both sodium and potassium chlorides by either floating or depressing the potassium mineral. In the process, the crude sylvinite is mixed with the saturated brine to remove most of any clay impurities that may be present. Then a flotation reagent is added and the pulp is sent to flotation cells where the sylvite is separated from the halite. The halite fraction is pumped to a tailings storage area, and the sylvite concentrate is dried.

Fractional crystallization is also more than a simple physical process and is based on the different solubilities of sodium chloride and potassium chloride in a saturated sodium chloride brine. In the treatment, such a brine selectively dissolves the potassium chloride. The brine is then cooled, and the potassium chloride is crystallized as a 99 percent pure product. *Langbeinite,* another potassium salt produced in the Carlsbad area, is separated from halite, its principal impurity, by a similar process involving the selective solution of halite. Potassium compounds are recovered from brines by evaporation and fractional crystallization, which involves the separation of sodium salts in triple-effect evaporators, leaving a hot liquor rich in both potash and borax. Rapid cooling under a vacuum then causes the potassium salts to crystallize, and they are subsequently removed by either settling or centrifuging.[136]

Sodium compounds mined in the United States are processed in a variety of ways. Most salt (sodium chloride) produced by underground mining receives no treatment other than the removal of tramp iron (usually blasting wire) with magnetic separators, plus some crushing and size grading. Evaporated salt produced from sea water and from natural or artificial brines is processed by solar evaporation, as well as by evaporation with the use of fuel.

In the solar evaporation method of producing salt, the first step involves flooding a concentrating pond with salt-bearing water and letting it evaporate until it reaches a specific density. As the brine reaches the desired density, most of the calcium and iron compounds precipitate and the brine is then transferred to a crystallizing pond. In the crystallizing pond, the brine is further concentrated to a greater density, at which point virtually nothing but

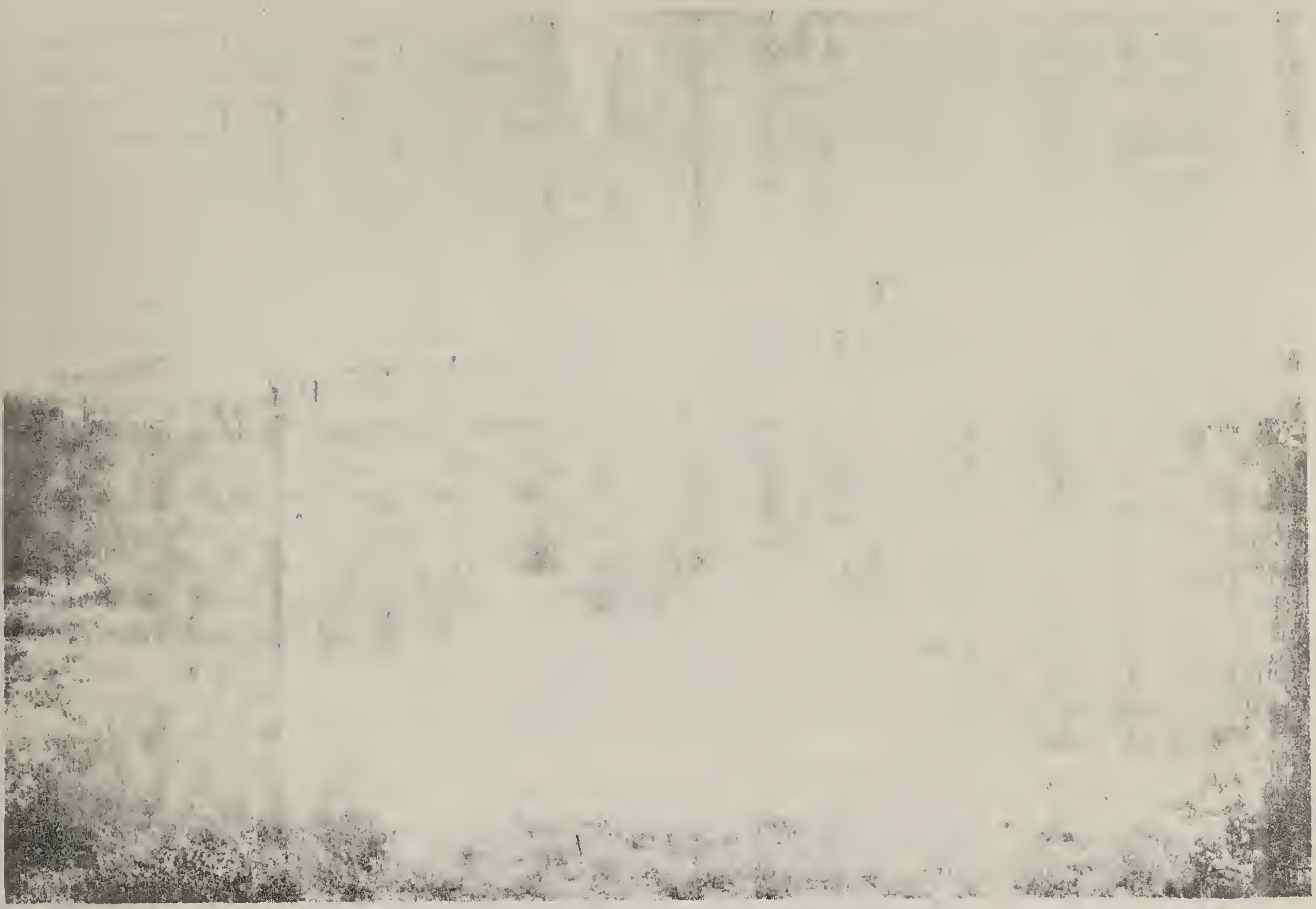


Fig. 81 - Cement plant in the Southwest. The manufacture of cement has become one of the major uses of limestone produced in the West. Such use is strongly related to local market conditions. It requires that raw limestone and other industrial minerals of proper characteristics and suitable location be subjected to both beneficiation and advanced processing treatment.

sodium chloride is deposited on the flat, smooth bottom of the pond. As further concentration of the brine beyond a particular point causes an excessive crystallization of magnesium salts, the remainder of the brine (*bittern*) is either wasted or further treated for the recovery of magnesium and bromine compounds.

The salt is removed from the crystallizing pond once a year by specially designed machines and delivered to a washing plant. The salt is washed with saturated brine, followed by a fine spray of fresh water, and is stockpiled. Most of the crystallized salt produced in the United States is marketed as undried crude salt, containing 99.4 percent sodium chloride. The remainder is kiln dried to 99.8 percent sodium chloride and vacuum-refined salt with a purity of 99.9 percent sodium chloride.

The entire production process using solar evaporation requires the use of extensive amounts of land in order to provide the maximum exposure of brine surface to the sun and the atmosphere. Other evaporation methods are used, however, that require less land but involve the use of far more complex equipment. In evaporation using fuel, the two main types of evaporators used by the salt industry are vacuum pans and grainers. Vacuum pans produce fine granulated cubic crystals, whereas grainers produce larger hopper-shaped crystals that are required in the processing of some foods and in other uses demanding a high rate of solubility.

Both solar and fuel-fired evaporation are also used in the processing of other sodium minerals. The natural form in which sodium carbonate occurs in nature is either in solution (brine) or as a solid mineral of which *trona* is the most prevalent. Each type of deposit requires a specific processing method to handle its own special situation to best advantage.

Mined trona is usually dissolved, making an artificial brine, and recrystallized, thereby eliminating many of the insoluble impurities and permitting the recovery of sodium carbonate crystals of the desired form. In the treatment of natural brines, the brine is usually first evaporated by solar means to as high a concentration as possible. The subsequent recovery of sodium carbonate crystals is then accomplished by direct crystallization (if sufficient sodium bicarbonate is present), by low temperature crystallization (to precipitate sal soda), or by the absorption of carbon dioxide (to precipitate either trona or sodium bicarbonate). After much of the sodium carbonate salt has been precipitated by one or another of these methods, the residual brine may be either recycled, discarded, or further processed. [137]

Vast tonnages of natural sodium sulfate are available from a great number of deposits in the Western States. In these deposits, sodium sulfate occurs as a natural brine or as solid masses. Most deposits are composed of a mixture of minerals, but many are essentially pure sodium sulfate. As with nearly all industrial minerals, each deposit requires a specific processing method to handle its own special situation to best advantage. Some producers of sodium sulfate mine relatively clean Glauber's salt (*mirabilite*) and dehydrate it. The processes of producing *thenardite* (salt cake) and *mirabilite* from natural deposits have become highly technical and are used with some complex brines to produce other products in addition to sodium sulfate.

The effect of temperature on the solubility of sodium sulfate in water plays an important part in its production and purification from brines. Mirabilite's solubility increases up to 90 degrees F, but above this temperature the thernardite form becomes the stable phase and its solubility is inversely related to temperature. Thus, fractional crystallization of Glauber's salt from the salt cake form of sodium sulfate is possible. The direct solubility-temperature relationship of mirabilite below 90 degrees F is used to crystallize it from brines merely by chilling. Brines are sometimes sprayed into the cold winter air at some properties or pumped into shallow surface ponds when outdoor temperatures are low enough to cause the crystallization of mirabilite. These crystals are then gathered and dehydrated. Because maximum surface exposure to the atmosphere is desired, these methods also require considerable land area that is directly related to the volume of production.

9. Advanced Processing of Metals

The advanced processing methods used in the production of metals from their ores also involve relationships between the amount of surface area used and the volume of production. The surface area requirements of metallurgical processes, however, are not usually as directly proportional to the volume of production as they are in the treatment of industrial minerals. Often the initial or minimum requirements for even a small amount of metallurgical processing are substantial. For large properties they are greater, but not necessarily in exact proportion to the greater volume of production.

The large minimum space requirements for most metallurgical processing plants is a reflection of the complexity of the processes and the heavy use of elaborate machinery and equipment. For most of the base metals, the advanced processing of beneficiated ores involves operations similar to those shown in Figure 82 for the smelting of iron and the subsequent production of steel.

One of the first unit operations used where wet metalliferous concentrates are the principal raw material is *drying*. Drying is commonly done by bringing the wet material in contact with the hot gas or air found in a drying furnace or kiln, and is often either followed by or is itself a part of roasting.

Roasting is the heating of an or concentrate to effect some relatively simple chemical change and is akin to calci in the treatment of industrial minerals. Its primary purpose is to convert metallic sulf s into other forms (e.g., oxides, sulfates) that are amenable to subsequent treatment There are oxidizing, reducing, chloridizing, and sulfatizing roasting processes, but it is usually an oxidizing process, used primarily to oxidize sulfide mineral with air to facilitate later smelting.[138] A reducing roast consists of heating an ore or concentrate in contact with coal or other reducing agents. A chloridizing roast is used to convert certain metals into chlorides by roasting in contact with chlorine gas, sodium chloride (salt), or other chlorine bearing compounds. A sulfatizing roast is a modification of the oxidizing roast.[139]

In addition to its primary purpose, roasting may perform other functions such as the removal of certain impurities by the volatilization of their oxides. These impurities include (in most ores) sulfur, arsenic, antimony, tellurium, and selenium. A reducing roast is often employed to convert iron-bearing nonmagnetic compounds into magnetic compounds as a preliminary process to magnetic concentration. Nonmagnetic *hematite* (Fe_2O_3), for example, may be converted into *magnetite* (Fe_3O_4) by employing a reducing roast. The four most common methods of roasting in current use are hearth roasting, flash or suspension roasting, fluidization, and blast or sinter-roasting. All of these generally involve the creation of considerable amounts of gaseous wastes.

Sintering is a process where heating causes an incipient fusion of previously divided solid particles. Some materials are normally given a sintering roast, such as in the use of Dwight-Lloyd machines for processing lead sulfide ores and concentrates. Sintering, however, is not necessarily roasting.

Distillation also involves the heating of metals or metallic compounds, but to the point of vaporization, and the subsequent recovery of the vapor in condensers as a liquid or solid. Distillation processes are used only for metals or metallic compounds which have relatively low boiling points, such as mercury, cadmium, and zinc.[140]

Smelting is any metallurgical operation in which metal is separated by fusion from those impurities with which it may be chemically combined or physically mixed.[141] Smelting is an ancient art, and it is interesting to note that copper was reduced from ores by smelting prior to recorded civilization and that iron ore was smelted before the year 3500 B. C.[142]

The products of a smelting furnace are in a liquid state except for the dust and fumes which are carried out in furnace gases. Crude metal and slag are the principal liquids produced in a reduction smelting process, usually performed in a blast furnace. Liquid *matte* and *slag* (waste materials) have different specific gravities and are immiscible liquids. They are now usually produced in a reverberatory furnace, and this process is sometimes called matte smelting.[143] Today, iron smelting represents the most important use of blast furnace reduction smelting. The smelting of copper concentrates is an example of reverberatory matte smelting. Both produce substantial amounts of gaseous wastes as well as the liquid slag which solidifies to solid waste upon cooling.

Smelting processes produce liquid impure metal and liquid matte which must be treated further by a process known as *converting*. This is a process of removing the impurities from molten metal or metallic compounds by blowing air through the liquid. The impurities are changed either to gaseous compounds, which are removed by volatization, or to liquids, which are removed as slag.[144] In converting, the creation of both gaseous and other wastes is involved, but not nearly as much as in smelting. Converting is carried out in a special furnace known as a converter and serves either to remove carbon, silicon, manganese, and phosphorous from molten pig iron, or to remove sulfur and iron from the molten mattes formed in smelting nonferrous sulfides.

Fire refining includes a number of processes for the purification of the relatively impure metals produced in nonferrous smelting and converting. Many impure metals require such refining to produce an acceptable grade of material to meet market requirements. Steel-making is essentially a fire refining process, but it is quite different from nonferrous fire refining because the end product in steel-making is an iron alloy and not pure iron. In

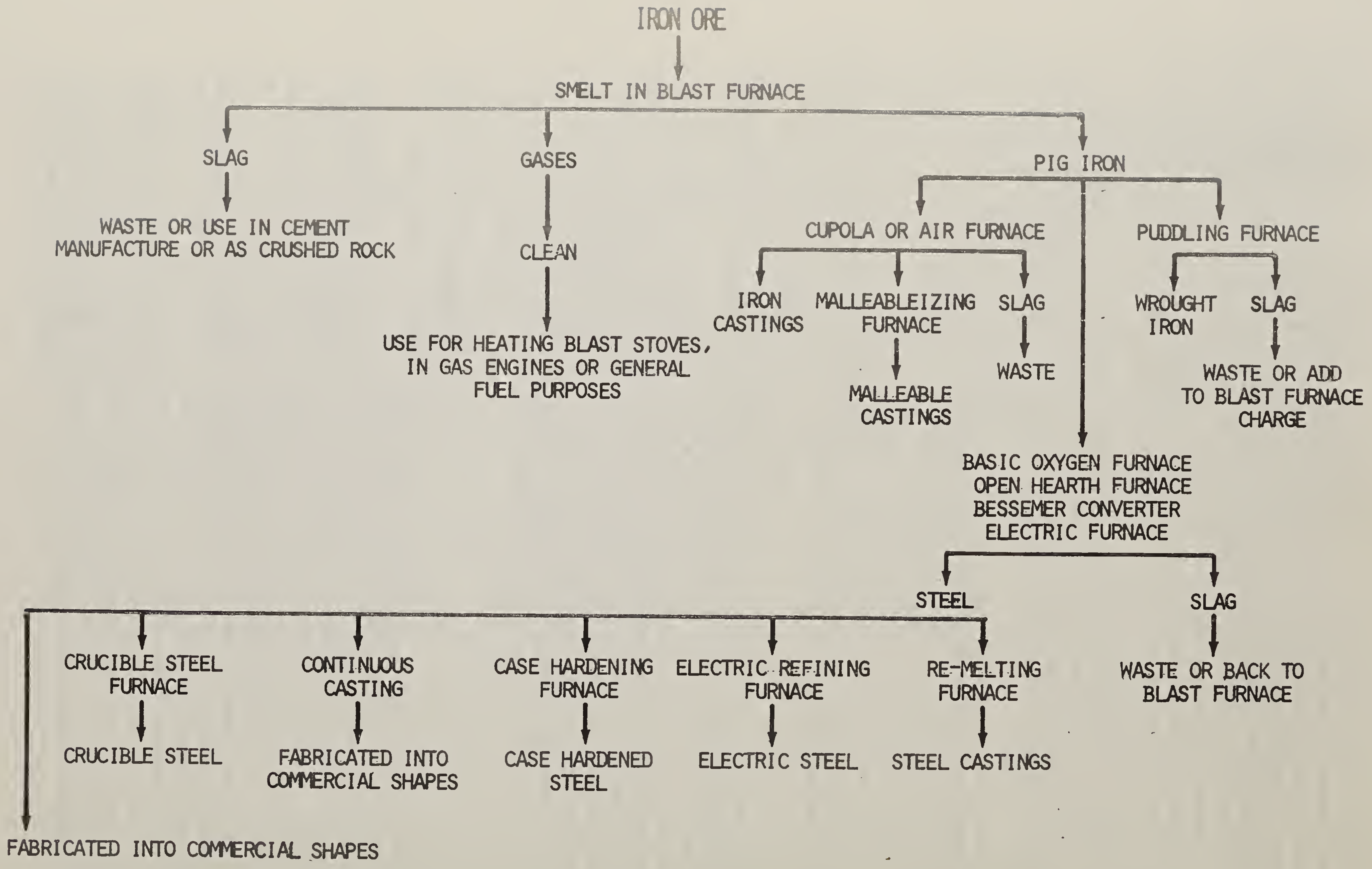


Fig. 82 - The advanced processing of iron ore to produce a useable metallic product involves many unit operations also found in the advanced processing of other metallic ores and some industrial minerals. Various waste commodities are a necessary result of these operations.

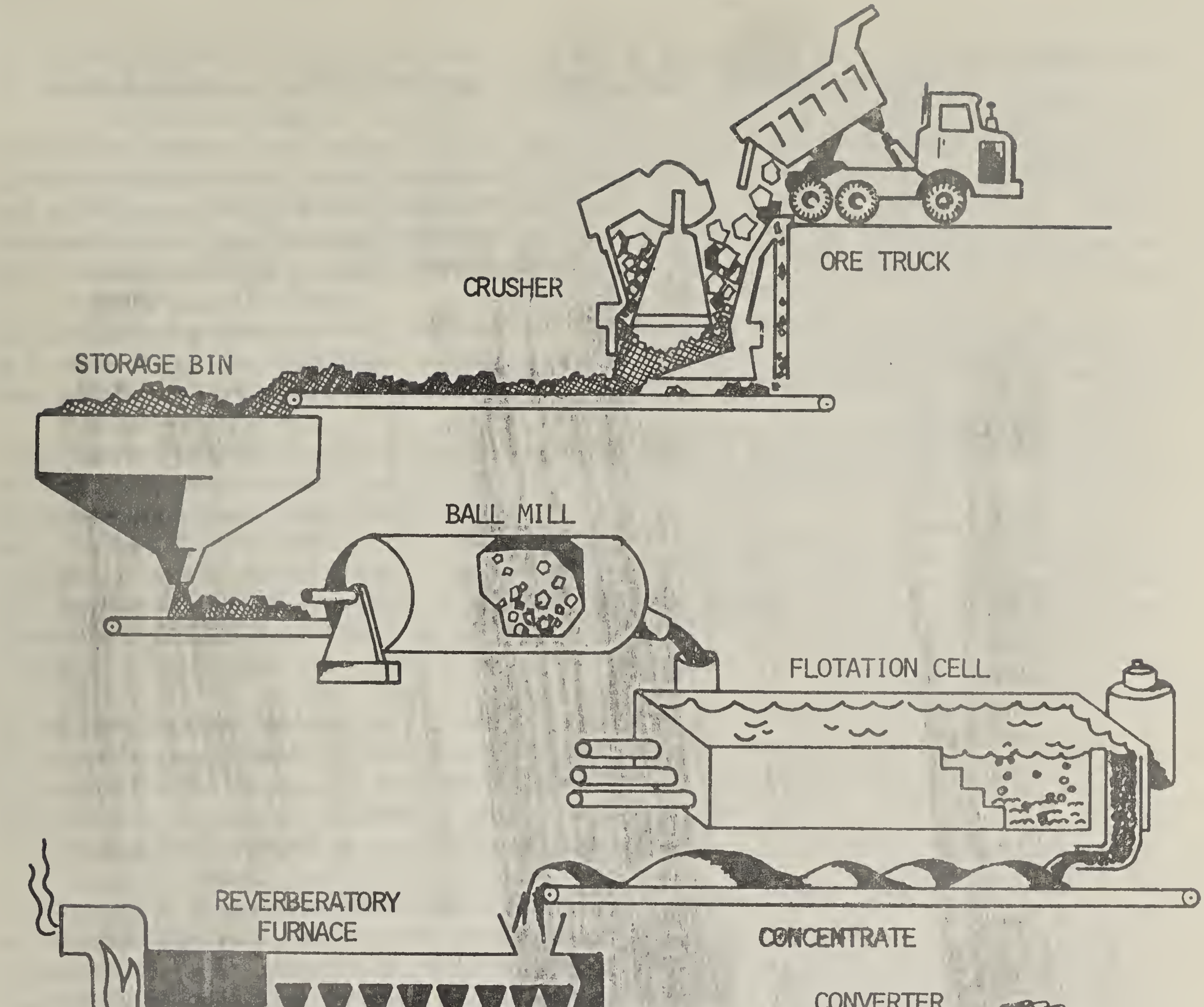


Fig. 83 - Diagrammatic representation of the beneficiation and advanced processing phases of copper production. Many of the operations now used in copper processing are also used in the production of other metals and some nonmetals. Virtually all nonfuel minerals production involves a similar flow of material through various stages of beneficiation and advanced processing to yield a marketable product. Much of this work must be done at or near the mineral deposit.

nonferrous refining, however, crude metal is processed into a standard grade of commercially pure metal.

Hydrometallurgical and electrometallurgical processes are also commonly used in the treatment of metallic ores and in refining impure metals. The hydrometallurgical methods are in many ways similar to those in use in processing industrial minerals and in the extraction of metals by leaching as has been described previously. All such processes require adequate supplies of water, but few generate any appreciable amount of liquid waste, since most is recycled in the process to gain efficiency.

Electricity is a common component of present-day advanced treatment methods. In producing some metals, the electric furnace has gained widespread use, but in these it is merely another source of heat. Electricity is used more directly in electrolytic refining and electrowinning.

The *electrolytic refining* process involves suspending suitably shaped metal ingots, known as *anodes,* in an electrolytic bath. Placed between the anodes are sheets of the same metal in a refined state which act as starters or *cathodes.* Direct electric current is applied to the plates, moving through the anodes, then through the electrolytic bath and into the cathodes. As the electric current passes through this circuit, the metal to be won is dissolved from the anodes and is electrolytically deposited on the cathodes. During this process, the impurities in the anodes are detached and either fall as slime to the bottom of the tank containing the electrolyte or are dissolved in the electrolyte from which they must be subsequently removed.

The electrolytic extraction (*electrowinning*) of metals from purified leaching solutions is similar to the refining process. The layout of tanks and electrical connections is similar to the electrolytic refining process, but the anodes are made of a material that is insoluble in the leach solutions. Antimonial lead anodes, for example, are usually used in the electrowinning of copper. The cathodes and starting sheets are similar to those used in electrolytic refining.

In electrowinning, leach solution is continually being added to the tanks as the metal is being deposited on the cathodes. Electrolyte which still contains considerable metal is reused for leaching more metal-bearing material, because it normally has a high free-acid content. Nevertheless, as impurities are also dissolved in the leaching process, they build up in the acid electrolyte because of this reuse, and these impurities must be periodically removed.

The electrolysis of igneous fusions is primarily used for the extraction of metals from their molten salt solutions. Some of the active metals such as aluminum, magnesium, radium, sirconium, and titanium are extracted and refined by this method. The electrolytic process for extracting and refining metals from their molten salt solutions is performed in a cell, the shell of which is used as a cathode. In some cases a carbon shell lining serves as a cathode. Anodes made of carbon or graphite are suspended into a molten electrolyte. Electric current is passed into the anode through the electrolyte and into the cathode. Metal is liberated at the cathode where it collects in a pool of oxygen and is usually liberated at the anode where it combines with the carbon of the anode to form carbon monoxide and carbon dioxide. During electrolysis, the electrolyte remains molten because of the heat generated by the resistance it offers to the passage of electric current. Sometimes, however, the required temperature for the electrolysis of molten electrolyte must be maintained or controlled by heat supplied from outside the cell.

10. Other Advanced Processes

The input materials for the electrolytic production of metals are not always those thought of as metallic ores. Sodium metal is produced by advancing salt (sodium chloride) to an electrolytic process. Almost all sodium metal is produced in the United States by the electrolysis of sodium chloride in a Downs cell, in which salt is fused and electrolyzed, yielding chlorine at the anode of sc n metal at the cathode. As in other metal production methods, gaseous wastes are a comr and frequently abundant by-product.

In a similar manner, other prc s techniques commonly thought of as used only on metallic ores are also employed in ti ting industrial minerals. For example, phosphate rock is decomposed by three fundamental methods in order to obtain products suitable for fertilizers and industrial purposes. These three methods include acid treatment, thermal reduction, and thermal treatment without reduction. In the *acid treatment process,* beneficiated phosphate rock is mixed with sulfuric, phosphoric, or nitric acid, or with some combination of the three.

Treating phosphate rock with sulfuric acid produces either ordinary superphosphate or phosphoric acid. If ordinary superphosphate is desired as a product, enough sulfuric acid is added to high-grade phosphate rock to convert the phosphate into water soluble monocalcium phosphate. Calcium sulfate is also produced as a by-product which may or may not be useful. It is not usually separated from the mixture. To produce phosphoric acid, additional sulfuric acid is added, and the resultant phosphoric acid is filtered from the insoluble calcium sulfate mixture.

Treating phosphate rock with phosphoric acid produces triple superphosphate. Phosphoric acid may also be combined with potash or ammonia to produce highly concentrated fertilizer salts, such as potassium phosphates or ammonium phosphates. Using nitric acid or a combination of nitric and another acid for the treatment of phosphate rock has not been used extensively in the United States. The resulting product, because of the calcium nitrate content, must be further treated, usually with ammonia, to produce a suitable fertilizer product.

The *thermal reduction method* involves the smelting of phosphate rock (i.e., phosphorus ore) with carbon (as coke) and a siliceous flux, usually in an electric furnace. The resulting products are elemental phosphorus, ferrophosphorus, carbon monoxide, and calcium silicate. The elemental phosphorus is then volatilized, condensed, and collected under water as a heavy liquid. The calcium silicate is tapped from the furnace as a molten slag. Small quantities of ferrophosphorus, produced from the iron in the original phosphate rock, are tapped from the furnace and marketed as a by-product. Phosphoric acid is subsequently produced by burning the elemental phosphorus and hydrating the product. The phosphoric acid is then usually converted into various fertilizer or industrial phosphorus compounds. Calcium metaphosphate is produced by burning the elemental phosphorus in a chamber into which pulverized phosphate rock is blown. The phosphate rock and phosphorus oxide react to yield molten calcium metaphosphate, which is then tapped and cooled.

In the thermal treatment of phosphate rock without reduction, several processes are currently used. One entails heating phosphate rock with alkali salt such as sodium carbonate with or without substantial defluorination, while a second variation involves heating phosphate rock in the presence of water vapor to defluorinate the rock as completely as possible. Still another method is the fusion of phosphate rock mixed with magnesium silicate (as serpentine or olivine). The resulting products are usually not treated further (except for grinding and sizing) before their use as agricultural chemicals.[145]

The greater complexities of the advanced processing methods used in producing both metals and industrial minerals have resulted in substantial increases in the cost, time, and space requirements of minerals production. For virtually all commodities, the methods and techniques now used to turn out a final product require greater amounts of more complex and expensive equipment, which in turn occupy greater land areas than the relatively simple processes of 1860.

11. Scale of Production

Despite the increased complexities and financial requirements of modern mineral production, the relatively small minerals producer has remained an important factor in the industry. For some mineral commodities, small operators are the only domestic source.

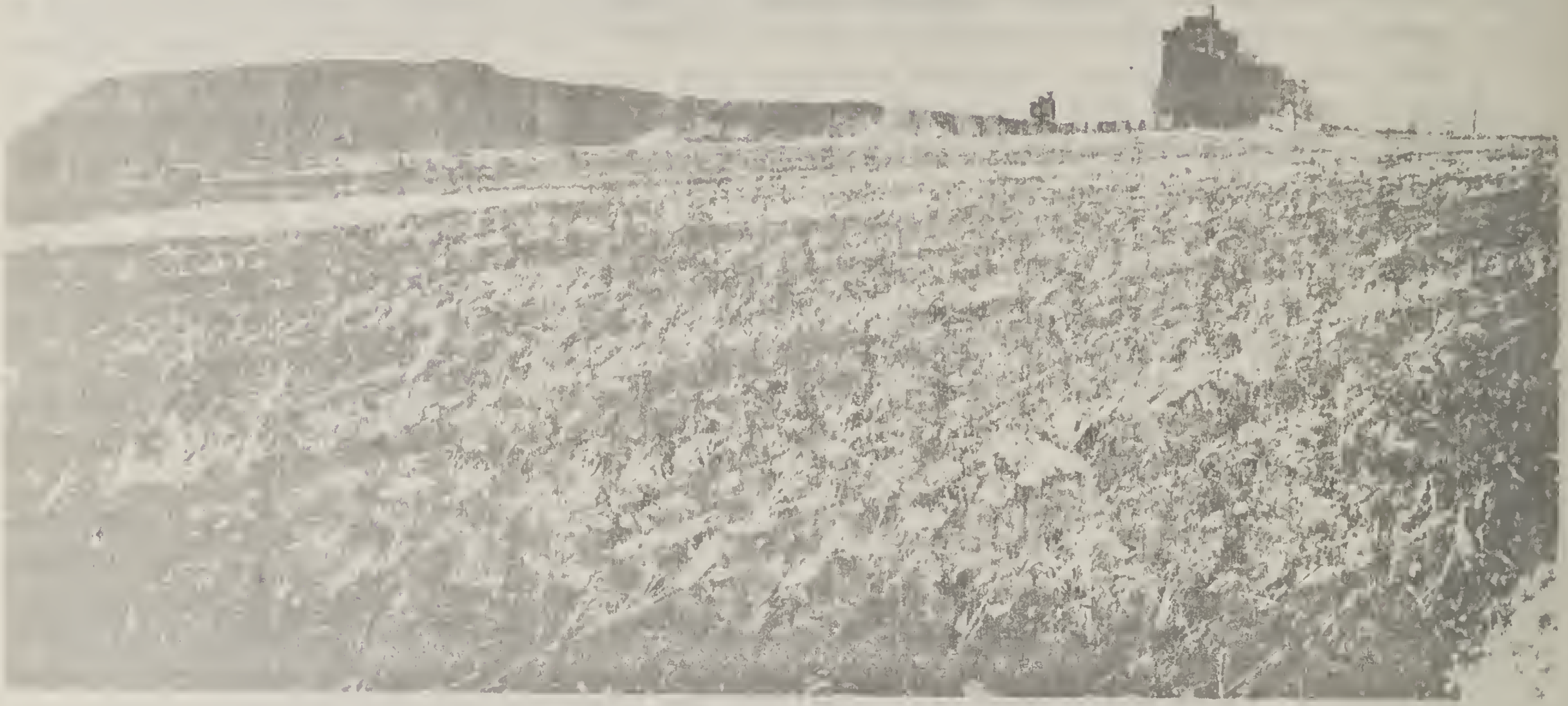


Fig. 34.–Elemental phosphorus plants such as this near Soda Springs, Idaho, used advanced processing methods that are more commonly thought of in connection with metallic ores rather than industrial minerals such as phosphates. The waste slag is also a frequent source of other valuable mineral products.

Of course, what constitutes a small mine is an arbitrary matter. In general, a *small mine* may be defined as one with a production of less than 300 tons of ore per day. A *medium-size mine* would have a daily rate of production ranging from 300 to 3,000 tons per day, while a *large mine* by today's standards would have a daily production of more than 3,000 tons. Technology has created an additional type since the early 1900's, however, and this could be termed the *very large mine*, with production greater than 30,000 tons per day. Another category that existed prior to 1872, the *very small mine* with a daily production of 30 tons or less, has virtually disappeared.

Using this arbitrary classification, most underground mines in the United States are in the small to medium-size class. Probably no more than 20 of the nation's underground mines produce an average of more than 3,000 tons per day. The country's two largest underground metal mines are block-caving operations which have capacities of around 40,000 tons per day each. Magma Copper Company's San Manuel mine produces an average of over 40,000 tons per day of low-grade copper ore and is presently being expanded. The mine at Climax, Colorado, operated by American Metal Climax, Inc., produces more than 40,000 tons per day of low-grade molybdenum ore. Most of the larger underground mines in the United States produce from 3,000 to 9,000 tons of ore daily.

Open-pit mines vary greatly in size, from those handling less than 100 tons of ore per day to the great Bingham pit of the Utah Division of Kennecott Copper Corporation which handles more than 100,000 tons of ore per day. Most open pits in the United States produce over 300 and many will exceed 3,000 tons per day. Of the nation's 15 largest open pit operations, all have capacities in excess of 15,000 tons of ore per day and nearly all commonly handle over 50,000 tons of combined ore and waste daily.

There is a relationship between the mineral commodity produced and the normal size of the production operation. This relationship in turn is based in part upon the natural mode of occurrence of the mineral and the unit value of the product. At the present time, the only mines that tend to be large-scale operations of over 3,000 tons per day are producers of copper, iron, and molybdenum ores. Typical of the copper mines are the porphyry operations in Arizona, New Mexico, Nevada, and Utah. Most of the large iron mining operations, however, are in the Lake Superior district, although there are also such operations in California and Utah. The big molybdenum mines are only three in number, two in Colorado and one in New Mexico. Molybdenum is a common by-product of porphyry copper mining, however, which also tends to be of large scale.

Mineral commodities that still tend to support smaller mining operations are numerous and include chromium, manganese, mercury, silver, tungsten, and uranium. The domestic mining of chromite is sporadic and of very small scale. Only 300,000 short tons of manganese ore and manganiferous ore was produced from three western states and Minnesota in 1967. This was an average of less than 1,000 tons per day total output of all mines. Although domestic mercury production was up in 1967, less than 440,000 short tons of ore were produced at 122 mines, an average of less than 15 tons per day per mine.

Idaho's Sunshine Mine, the nation's leading silver mine, usually produces less than a thousand tons of ore daily. The Clayton silver mine in Idaho produced a record of 74,000 tons of silver ore in 1967, more than twice the average production of the previous six years, but only about 200 tons per day. Much of the country's silver production also comes from lead and zinc mines which are likewise frequently small to medium-size operations.

Tungsten mines tend to be small and to operate sporadically depending on the metal's price. An exception is the Pine Creek Mine of the Union Carbide Corporation near Bishop, California, which produced at a rate of about 1,500 tons of tungsten ore per day in 1967. Uranium mining is also typically small. Approximately 500 uranium mining operations in eight states produced nearly 5.3 million tons of ore in 1967, an average of only 30 tons per day per mine. Several New Mexico uranium mines produced as much as one million tons in 1967 (3,000 tons per day), but these are exceptionally large uranium mines.

Many mineral commodities are now produced by both large and small operations. Metallic mineral commodities that support small, large, and medium mining operations in the United States include bauxite, gold, lead, titanium, and zinc. Domestic bauxite mining operations tend to be small to medium in size, with over 95 percent of total United States output coming from mines operated by three companies in Saline County, Arkansas. Two large gold mines, the Homestake in South Dakota and the Carlin in Nevada, contributed nearly two-thirds of the total domestic gold production in 1967, and a significant production of gold comes as a by-product in the large-scale mining of copper. Nevertheless, there continues to be a small but dwindling number of small gold mines in the West. One of the smallest of the nation's gold producers is an individual in Central California who collects gold flakes from riffles placed in commercial sand and gravel operations on the San Joaquin, Merced, Tholumne, Mokelumne, and American rivers in California's original placer gold country. Although operating as an individual entrepreneur on a "sharecrop" basis with the sand and gravel producers, he grosses between $4,000 and $6,000 per month, with his own labor and transportation virtually his only cost items.[146]

Lead is mined in several Western States but almost half of the nation's production comes from Missouri, where two St. Joseph Lead Company mines produce about 3,000 tons of ore daily. The 25 leading zinc-producing mines in the United States in 1967 produced 75 percent of total domestic zinc production. Each of these mines normally produces about 300 tons of ore daily, but a few occasionally produce more than 3,000 tons per day.

Industrial minerals that are commonly produced in quantities exceeding 1,000 tons daily include Frasch process sulfur, phosphate rock, potash, and rock salt. The 13 Frasch process mines in operation in the United States in 1967 produced almost eight million long tons of sulfur, an average of nearly 2,000 tons per day per mine. All of this production came from Louisiana and Texas. Most of the nation's phosphate rock production comes from large mining operations in Florida. The largest western operation, J. R. Simplot Company's Gay Mine in Southeastern Idaho, produces about 5,000 tons daily. Several potash mines in New Mexico, producing from about 3,000 to nearly 10,000 tons of crude rock daily, contribute almost 90 percent of total domestic output. Other states producing potassium salts on a large scale are California and Utah.

Rock salt is mined by underground methods on a large scale in Michigan, Texas, New York, Louisiana, Ohio, Utah, New Mexico, and Kansas. The room-and-pillar method is generally used, which permits a high degree of mechanization. Salt production by the solar evaporation of brines and from solution mining tends (in the United States) to be on a smaller scale than the production from conventional underground mining methods.

Industrial minerals used in construction and in minor chemicals with relatively small demand are usually mined on a small scale. Most of the barite mined before the 1940's came from residual deposits which were small, and thus, the mining operations were of small scale. There is, however, a growing number of larger operations in bedded replacement deposits, a few of which now approach 3,000 tons of ore production a day.

The mining of fluorspar from fissure veins and from residual deposits tends to be sporadic and on a small scale. The Illinois-Kentucky district has been the world's largest producing area, but few mines there produce more than 1,000 tons per day.

The first commercial output of perlite in the United States was reported in 1946. In 1967, more than 600,000 tons of crude perlite were mined at 18 operations in nine Western States, for an average of less than 100 tons per day per property. Similarly, pumice and volcanic cinder production in 1967 totaled about 3.5 million tons, but production was from over 150 small operations scattered over 15 states. Average mine output was only about 60 tons per day. Other construction materials operations including those producing gypsum, limestone, and other crushed stone, as well as sand and gravel, are also relatively small, although large operations are not uncommon as shown in Figure 85.

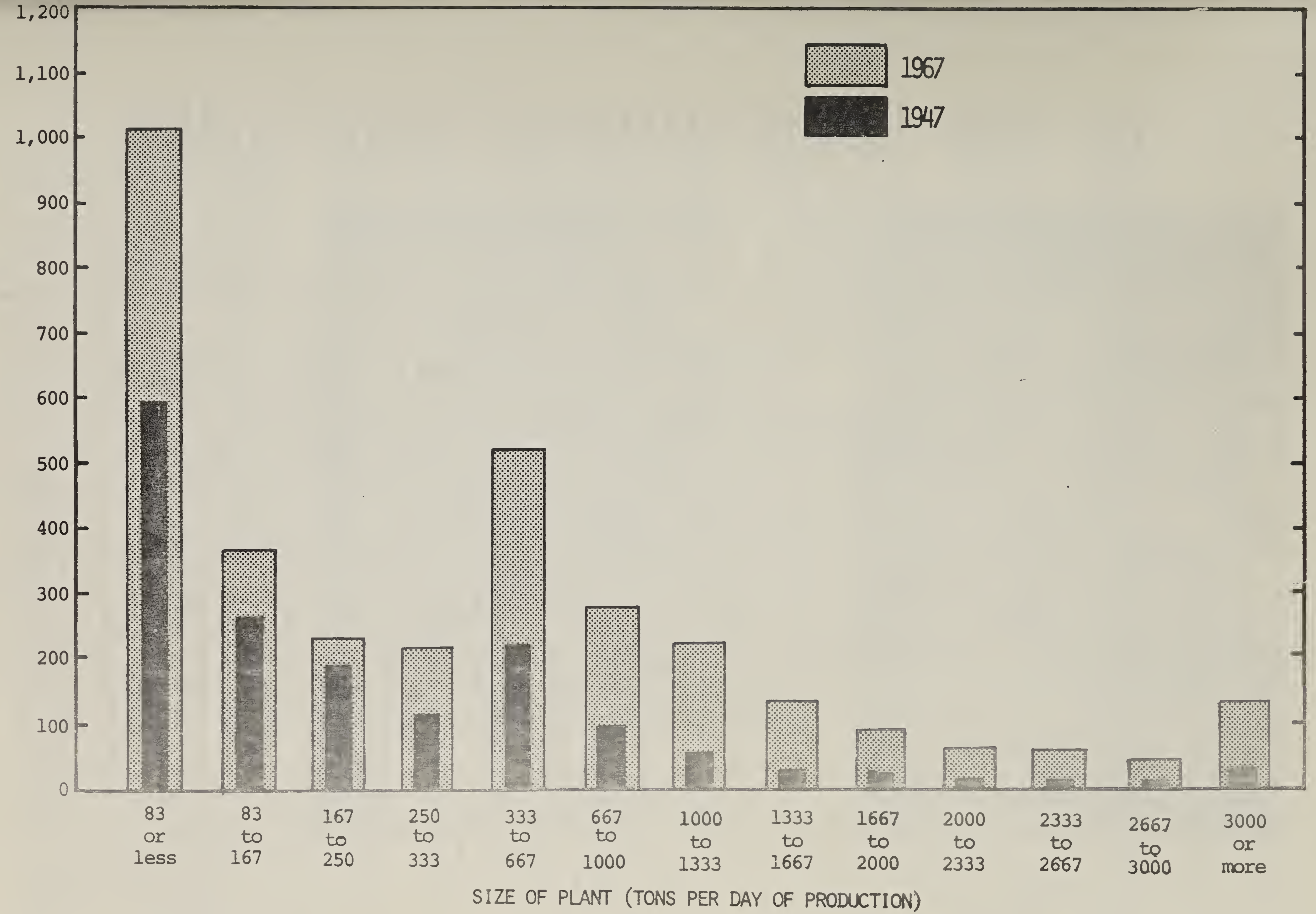


Fig. 85 - The size distribution of crushed stone plants in the United States has continued to reflect the importance of the small producer on the industrial minerals sector of the nation's economy.

F. CHANGES IN MINERAL PRODUCTION TO 1985

1. Expected Changes in Mining Operations

There is little doubt that changes will take place in the production of nonfuel minerals in the United States between now and 1985. Some of these changes will be evolutionary, while others will be truly revolutionary. Some aspects of the industry will probably remain virtually unchanged.

The biggest changes in minerals production will probably come in mining operations, although there should also be significant advances made in beneficiation and advanced processing as well. The greatest single change in mining will be the shifts from one general type to another. In most cases, this will involve a shift from underground to surface mining, but in some cases it may entail a change to some yet untried method. There will also be changes, some small, some substantial, within the mining systems themselves.

Actual changes within mining methods themselves will probably not be great in the next 15 years, but mining unit operations will, in general, grow larger with larger equipment and greater mechanization resulting in higher labor productivity. For the most part, changes in mining methods will be instigated by the availability of new high-capacity mining equipment. Trends in use of mining methods are expected to continue in the same direction as in the past 20 years, i.e., toward the increased use of lower-cost bulk mining methods. The exhaustion of higher-grade ore deposits, ever increasing unit labor costs, and society's insatiable demand for minerals combine to make this trend inevitable.

The recent development of higher-speed trackless mining equipment and the potential for the low-cost boring of drifts should make the room-and-pillar and stope-and-pillar methods persistently popular in appropriate mineral deposits. Block-caving should continue to produce more tonnage than any other underground method. Several new large block-caving operations are even now in various stages of planning. Longwall mining also shows considerable promise for certain commodities if continuous hard rock excavators can be adapted to this service. Of all the conventional mining methods, longwall mining lends itself best to totally remote controlled or even automated operation. Both it and block-caving, although underground methods, result in the disturbance of the overlying and immediately adjacent surface areas. This will continue to be a problem for surface land use, but may also encourage the increased utilization of leaching methods and thus a more complete utilization of the valuable mineral resources in a given deposit.

There are likely to be many changes by 1985 in mining equipment. The relentless battle for greater productivity is a continuing challenge to mining equipment manufacturers. It is difficult, however, to predict exactly what new mining machines will appear on the market in the next 15 years. It can be stated, nevertheless, that the characteristics of these new machines will generally be the same as those in other industries. They will result in higher productivity. They will be more expensive, more complex and sophisticated, and they will demand a higher level of competence on the part of maintenance personnel.

The competition between cyclic and continuous mining methods should be keen in the coming years, with continuous methods making more inroads in hard-rock mining. Even today a significant proportion of mine development openings are being bored rather than drilled and blasted. Such techniques will probably increase development capital requirements but reduce development time.

Nuclear explosives present an intriguing dilemma in offering extremely low-cost energy units, but with some severe and perhaps costly disadvantages. At present, nuclear fracturing for in-place leaching or solution mining appears to be the most promising application of nuclear explosives in the mining industry. Before 1985, nuclear explosives will probably be used in such an application, but this will undoubtedly be the exception rather than the rule. The large amount of unuseable energy in a nuclear explosion, plus the potentially hazardous side effects, will probably prevent *widespread* usage of such explosives in the Western United States within the next two decades. Nevertheless, in-place leaching of ore broken by

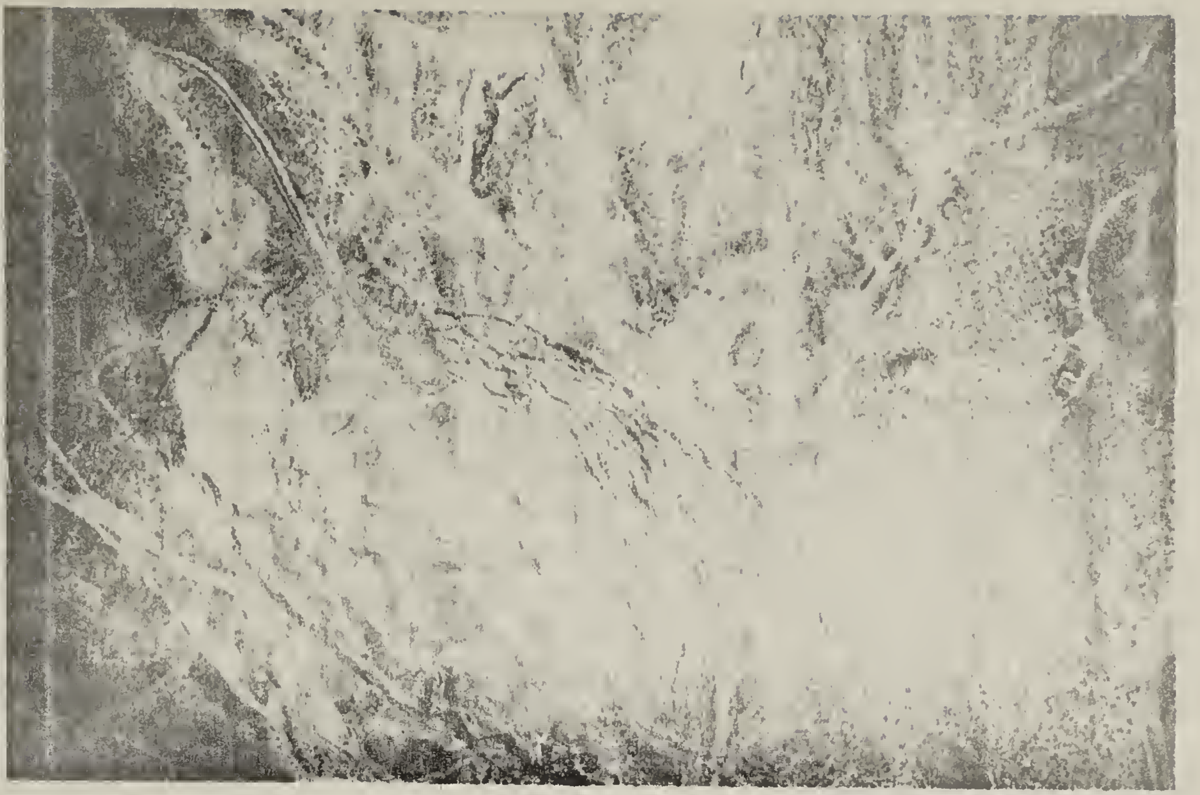


Fig. 86 - Underground mining with nuclear explosives will probably be in at least limited use in the Western United States before 1985. The use of such methods, as well as other underground techniques, can result in surface disturbance such as this mound of surface rubble produced by the underground detonation of a nuclear device. At top is surface subsidence resulting from block caving operations. (Photo courtesy of United States Bureau of Mines)

buried nuclear explosions is now under study and represents a potential for exploiting what are now submarginal deposits. Even now, nuclear devices with yields of 100 kilotons can be obtained in cannisters with outside diameters of only 11 inches.[147]

Winning minerals by leaching from what were once considered submarginal deposits is a growing factor today in total domestic metals production. At the end of World War II, the production of copper from leaching was only four percent of the total production. In 1963 leaching accounted for eight percent of total copper, and at its present rate of growth is expected to increase to 20 percent of total output in 1975.[148] Hydrometallurgical techniques now under development by a number of companies are expected to permit the extraction of metals other than copper and uranium in the near future. Potentially leachable are minerals of nickel, zinc, cobalt, and chromium.

Placer mining in the United States has been used mostly in the recovery of gold. Because of the fixed price of gold, the primary mining of gold has declined, but it is a trend that could change in the future under a higher gold price. Floating dredges have been one of the lowest-cost methods of placer mining, but many of the nation's placer deposits that are readily amenable to this method have already been worked one or more times. Those that remain are not likely to be mined soon by dredges because of restrictive legislation regarding stream pollution and rehabilitation. Small-scale placer operations have all but passed out of the picture, both because of the high cost of labor and because of restrictive legislation. In the 1970's, however, the West's once booming dredge mining industry could undergo some resurgence because of higher gold prices, but environmental control legislation and access to economic auriferous gravel deposits will undoubtedly have a major impact. There is one realm in which placer mining may again regain its previous significance. That is in continental shelf mining. As one authority has noted,

> Offshore placer deposits, other than those being mined, present a tremendous challenge and potential for exploitation when justified by economic conditions. The complex problems of search, prospecting, valuation, equipment and methods for mining, and beneficiation of minerals are being intensively studied by a number of government and private organizations. The Marine Minerals Technology Center of the United States Bureau of Mines, Tiburon, California, is one of the important agencies concerned exclusively with marine mining research. Initial successful ventures within the near future are a reasonable expectation, followed by gradual expansion as techniques are proved and costs and value of products can be estimated within satisfactory limits.[149]

2. Changes in the Importance of Different Mining Methods

In a strictly economic and technical sense, surface mining methods probably have the greatest potential in the future utilization of mineral resources in the West. Surface mining is generally more advantageous than underground mining in mineral recovery, grade control, economy, flexibility of operation, safety, and working environment. There are, however, many deposits that are too small, too irregular, and too deeply buried to be mined economically by surface methods. Furthermore, even where ore grade mineralization extends to a greater depth below existing open pits, the rapidly increasing amount of overburden to be handled imposes economic limits beyond which mining must either be abandoned or converted from open pit to underground operations.

In the production of minerals by surface methods, the greatest share is accounted for by coal, copper, iron ore, clays, gypsum, phosphate rock, sand, gravel, and stone. The future may also see this list extended to uranium because the potential of atomic energy as a source of power may create a demand for greatly expanded production of its minerals.

The character of the deposits of these mineral commodities should dominate the future development of and the choices to be made between surface and underground mining technology. Other minerals such as lead, zinc, potash, and salt will probably continue to be mined in large volume operations, but it appears unlikely that underground methods will be challenged successfully by surface mining because of the peculiarity of the physical environment in which such minerals are found.

Future available copper reserves are dominated by the porphyry coppers, and these will probably continue to be mined mostly by open pit methods until all relatively near-surface ores are exhausted. The deeply buried, bedded copper deposits of Upper Michigan will continue to be mined from underground.

The depths of existing open pit mines and the ratios of waste to ore are steadily increasing. Furthermore, open pit copper mining has been seriously challenged by block-caving. The minimum grade of ore necessary to sustain profitable production at several open pit copper mines is in fact higher than for the industry's principal block-caving mine. It will be technically and probably economically feasible for several of these open pits to convert to underground mining in the future. At the present time, however, neither the limits to the improvement of surface mining nor the potential for improvement of caving methods has been reached.

Domestic reserves of iron ore occur predominantly in enormous, massive, and thick-bedded deposits situated at relatively shallow depths, and substantial amounts of these reserves contain between 25 and 30 percent iron. The ability to market these low-grade ores economically has been dependent more on improved mineral beneficiation than on improved mining technology, although the latter has also been a significant factor. In Europe, technology of mining iron ore underground has advanced considerably, indicating that underground methods are nearly competitive for mining some types of iron ore deposits at greater depths. Nevertheless, the open pit mining of iron ore is likely to continue to dominate the future.

Future sources of most nonmetallic minerals will probably not differ significantly in physical character from those now being utilized. Deposits of stone suitable for commercial use are generally in the form of thick beds (e.g., limestone, dolomite, sandstone) or massive, igneous bodies (e.g., basalt, granite). Gypsum usually occurs in beds that are typically irregular and undulating, but relatively horizontal. Phosphate rock occurs both as horizontal, unconsolidated, post-marine surface deposits and as inclined beds within formations of other sedimentary rocks.

A great deal of the nation's limestone is already mined from underground at costs competitive with quarried stone, and it is technically and economically feasible to mine most thick-bedded or massive nonmetallic deposits from underground. This in fact is being done where the unit value of the product is sufficient to support underground mining and the geologic conditions make such mining necessary. It is likely that deep deposits of high-quality industrial minerals will continue to be mined underground, but it is also likely that new deposits near the surface will become more attractive, both technically and economically, in the future.

The mining methods used over the next two decades will probably vary considerably from one industrial mineral to another. Drastic changes in the relative importance of the several mining methods are not foreseen. For example, at the present time, nearly all of the nation's phosphates are mined by surface methods. Under the technical and economic conditions foreseeable by 1985, it is doubtful if the percentage of phosphate rock mined in the United States by surface methods will increase much above 99 percent. It could, however, go to 100 percent as early as 1975, and it probably will not drop much below 98 percent at any time over the next two decades. Drastic changes in the availability of near-surface deposits, however, could cause an increase in the importance of underground methods. This is a distinct possibility at least in the Western Phosphate Field of Idaho, Utah, Wyoming, and Montana.

If the trend in the relative importance of underground mining methods in the production of domestic potash that existed from 1947 to 1967 continues to 1985, then by

1985 the production of potash from underground mines should account for more than 94 percent of the United States total. The persistence of the 1947 to 1967 trend is not likely, however, under foreseeable changes in technical and economic conditions. Rather, it appears that a peak share for underground production of about 93 percent was reached in 1961. A more realistic forecast for 1985 would find underground methods accounting for between 85 and 90 percent of total United States production and perhaps as little as 75 percent. This change would reflect a significant growth in the use of solution mining techniques in potash production.

If the technical and economic conditions that have influenced the importance of underground mining methods in the production of sodium chloride salt in the United States since 1947 persist to 1985, then by that year underground mining methods should account for approximately one-third of total domestic production. It is highly likely, however, that the trend which should be projected to 1985 is that which has persisted from 1957 to 1967 under conditions of increasing demand for sodium chloride salt for both its sodium content and its use as a basic raw material in chemical and industrial processes. If the trend of only the last ten years is projected, then the proportion of salt produced from underground operations in the United States could climb as high as 45 percent by 1985 and will probably exceed 30 percent by 1970.

With the existing and expected increase in the emphasis on extracting harmful pollutants from industrial wastes, it is highly probable that the decline in the importance of Frasch process sulfur in the United States that has already occurred will continue to 1985. If, in fact, the technical and economic conditions which have affected the decline of the Frasch process since 1950 persist until 1985, then by that year probably no more than 80 percent of the nation's sulfur will come from Frasch process mines, and the proportion of such sulfur in domestic output could fall as low as 66 percent. It is more likely, however, that by 1985 approximately 70 to 75 percent of the sulfur produced in the United States will come from Frasch process mines.

This decline will not be a reflection of any particular inherent weakness in the Frasch process as a method of removing sulfur from the earth, but rather a reflection of the importance given to removing sulfur from the atmosphere. By 1985, about one-fourth of the nation's sulfur production will probably come from treating waste gases produced in the burning of sulfurous fuels such as coal and natural gas and in the reduction of sulfide ores of various metals. Changes in advanced processing methods in metallic minerals production will thus have a direct impact on nonmetallic mining methods.

Changes in the methods of base metals processing have already had effects on the mining of other metals and can be expected to do so even more in the future. The increased use of electrometallurgical processes is likely to have a pronounced influence on precious and rare metals mining.

If the trend which has persisted from 1947 to 1967 continues at its current rate, then the percent of gold produced from surface mining methods in the United States in 1985 should be between 41 percent and 63 percent of total United States gold production. This assumes, of course, that the basic conditions governing the variation in the percentage of domestic gold produced by surface mining methods will persist essentially as they did from 1947 to 1967 straight through to 1985. And this, of course, will probably not be the case.

A significant increase in the amount of gold produced from surface mining methods was caused by the introduction of gold from the Carlin, Nevada, deposit in 1965. Although other similar mines will come into production, it is not likely that there will be another major technological change in the production of gold in the United States before 1985. The initiation of production from the Carlin type deposits has been, in fact, the first major new development in gold mining since the 1850's. Therefore, the sharp rise in the proportion of gold produced from surface methods will probably not continue to rise at its current trend from 1967 to 1985, and gold produced as a by-product from advanced processing operations in copper, lead, and zinc, as well as silver production, will probably continue to be of major importance.

If the trend in the amount of gold produced from surface mining methods that persisted from 1947 to 1964 is projected to 1985, the proportion of gold produced from surface mines in the United States in that year should be about 30 percent. If the current level of production from surface mining methods is projected to 1985, at that time it should be slightly less than half of total United States production. This latter projection (i.e., the projection of current levels of production at the slope of the trend line which was achieved between 1947 and 1964) is the most likely forecast for the share of the nation's gold to be produced from surface mining methods in 1985.

The future development of large, relatively low-grade silver deposits such as those near Calico in San Bernardino County, California, could bring to the silver mining industry a technological change equivalent to that of the opening of the Carlin-type deposits in the gold mining industry. The initiation of the surface mining of such large disseminated silver deposits would undoubtedly increase substantially the amount of silver mined in the United States by surface mining methods. Under the assumption, however, that the conditions in the silver mining industry that affect the percentage of the metal coming from surface mines will persist to 1985 as it did from 1947 to 1967, then by 1985 approximately one-fourth of total United States silver output will come from surface mines. A major technological change, however, such as that involved in the utilization of large, relatively low-grade deposits would undoubtedly raise this well above 25 percent, and it could even go as high as 35 percent. Even with the introduction of the large-scale surface mining of silver within the next five to ten years, however, it is expected that the major portion of the silver produced in the United States in 1985 (i.e., two-thirds to three-fourths of the total) will still come from underground mines.

It is highly likely that new technological developments foreseeable in the copper mining industry may again cause a decline in the percentage of ore produced by traditional surface mining methods. The initiation of production at two large underground copper mines in the mid-1950's, thereby producing much larger amounts of copper from underground operations, is not considered to be just a sporadic occurrence, but a cyclical event. New technological developments in the underground mining of copper ore in the United States have occurred at rather frequent intervals and therefore may be expected to occur again before 1985. As a result, it is not appropriate to predict the importance of future mining methods solely on the basis of a trend established from 1958-1967, but rather on the longer term trend from 1947 to 1967.

Based on the projection of trends since World War II (and with confidence limits established at two standard deviations above and below the trend), it can be estimated that in 1985 the amount of copper ore produced in the United States from surface mining methods will fall between 82 and 94 percent of total domestic production. It should be pointed out, however, that even more drastic changes in mining technology, such as the large-scale introduction of solution mining with underground nuclear blasting, could drastically change this projection.

Surface mining will undoubtedly be of much greater significance in iron ore production than in any of the other base metals. If the conditions affecting the proportion of iron ore produced in the United States from surface mining methods that existed from 1947 to 1967 continues unchanged, virtually all of the iron ore produced domestically will come from surface mines well before 1985. In fact, 100 percent surface mining of iron ore domestically could be reached as early as 1970. It is more likely, however, that the 100 percent figure will be approached in the early 1970's and perhaps not until 1975. By 1978, virtually all of the iron ore produced in the United States should be coming from surface mines. These projections, of course, preclude any major technological or economic change which would again rejuvenate the importance of underground mining methods in the domestic production of iron. Such changes are likely to occur, but their influence and timing are unpredictable.

High unit value metals are less likely to be as dominated by surface methods as will iron. A projection of the overall trend followed by the relative importance of surface mining methods in uranium ore production in the United States from 1947 to 1967 yields a forecast that by 1985 the percentage of domestic uranium ore produced by surface mining methods should be about 55 percent of the total, but could go as low as 40 percent or as high as 60 percent. It is more likely, however, that a somewhat more gradual trend will be followed in the mining of uranium, which is still and will probably remain a relatively high unit value commodity. If the more gradual trend is projected, the percent of uranium ore mined in the United States by surface methods in 1985 will probably be somewhere around 40 to 45 percent of total domestic production. Major technological changes, however, both on the demand side for uranium and on the supply side, involving both the mining of and exploration for uranium deposits, could send the share of the nation's uranium mined by surface methods above 50 percent as early as 1970. Pressures for the reduction in the exposure of miners to radon daughters may accelerate the trend to open pit or solution mining of uranium by increasing underground mining costs.

The mining of mercury has been and will probably continue to be a rather sporadic venture with conditions, both economic and technological, changing abruptly and in different directions. If such does prove to be the case between now and 1985, or in other words, if the economic and technical conditions that existed from 1947 to 1967 continue to vary to 1985 as they have since the end of World War II, then by 1985 a little more than half of the mercury mined in the United States should come from surface mines. Actually, the total share could vary anywhere from 50 to somewhat over 60 percent. If, however, the developments that have taken place since the mid-1950's remain essentially unchanged, then by 1985 the proportion of mercury produced in the United States from surface mining methods will probably not be much above one-third and could be as low as only 20 percent of the national total.

Thus, although it can be assumed that markets for increasing amounts of mineral commodities will grow merely because of growth in population and per capita consumption, in view of changes that are already evident, it cannot be assumed that conditions will continue to favor any one particular method of mining over all others for all commodities. Rather, it is apparent that the relative importance of different mining methods in the production of metallic minerals, elements such as sulfur, and industrial minerals such as potash and phosphate has been changing and will continue to change at least until 1985. For some materials, the importance of underground mining methods has been increasing and may be expected to increase over the next 20 years. In other areas and for other commodities, surface mining methods are becoming much more dominant. For certain commodities, solution mining is entering the picture and may be expected to become more prevalent long before 1985. The relative importance of different mining methods is changing, and it does so with respect to the commodities being produced, their geologic settings, and the conditions of technology and economics.

Public policy already is exerting strong pressure favoring a reduction or elimination of certain methods of mining. This increasing force could become the deciding factor in determining the future trend in surface vs. underground vs. other types of mining.

The principal complaints regarding surface mining are evident. Many are critical of altering the natural aspect of the land by strip mining, open pits, quarries, or sand and gravel pits, by the accumulation of solid waste, by the pollution of streams with acids and fine solids, and by filling the atmosphere with dust. While it is thought by many that conversion to underground mining, or elimination of surface mining wherever feasible, would be a major step toward reducing many of these effects, it is often overlooked that the most economical and efficient methods of underground mining frequently result in disturbance of the overlying surface in a manner that is often erratic and sometimes unexpected.

3. Changes in Production from the Public Lands

Public policy will, of course, be most heavily felt by mineral industries operating on the public lands. The full extent of these industries, however, is not known. Because to date most mineral production from public lands for which adequate records have been kept involve those minerals that fall under the mineral leasing laws, most of the *known* production from public lands has been of industrial minerals and fuels. The most important of the industrial minerals produced on public lands since the end of World War II has been potash. In 1945 potassium mineral production from public lands was valued at approximately 25 million dollars. This has risen rather steadily (with only slight declines at periodic intervals) to nearly 110 million dollars in 1964. Since 1965, there has been a sharp decline in the value of potassium mineral production from public lands in the United States, with the value of the total output dropping to 70 million dollars in 1967, down from about 95 million in 1966 and almost 114 million in 1965.

If the trend which persisted from 1945 to 1965 is projected to 1985, then the total value of potassium mineral production from public lands in the United States in that year should exceed 200 million dollars. The validity of the projection of this trend as a forecast is questionable, however, because of the sharp decline in such production which has occurred within the last three years. As a result, no meaningful prediction of the value of potash production from the public lands in 1985 (or in fact even for 1970) can be made with the data currently available. The same is true for virtually every other nonfuel mineral commodity currently produced on the public lands of the United States.

FOOTNOTES

59/ California Division of Mines and Geology, *The Mother Lode Country,* Bulletin No. 141.

60/ Idaho Bureau of Mines and Geology, *Bulletin No. 18.*

61/ Washington State Department of Geology, *The Metal Mines of Washington, Bulletin No. 23.*

62/ J.F. O'Brien, *Copper in California,* San Francisco: California Division of Mines and Geology (1957), p. 85.

63/ Bantwell, *Report on Mines and Mining,* House Executive Document No. 211, 42nd Congress of the United States, Vol. 10, Washington, D.C.

64/ Bantwell, *Report on Mining Statistics,* House Executive Document No. 10, 42nd Congress of the United States, Vol. 1, Washington, D.C.

65/ *Ibid.*

66/ J. F. O'Brien, *op. cit.,* p. 174.

67/ K. Richards and J. Courtright, "Structure and Mineralization at Silver Bell, Arizona," *Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966), p. 157.

68/ R. T. Moolick and J. J. Durek, "The Morenci District," *Geology of the Porphyry Copper Deposits, Southwestern North America,* Tucson: University of Arizona Press (1966), p. 221.

69/ T. A. Rickard, *op. cit.,* pp. 347-353.

70/ C. H. Dunning, *op. cit.,* pp. 76-79.

71/ D. C. Bryant and H. E. Metz, "Geology and Ore Deposits of the Warren Mining District," *Geology of the Porphyry Copper Deposits. Southwestern North America,* Tucson: University of Arizona Press (1966).

72/ *Mineral Resources of the United States, Part 1: Metals,* U.S. Geological Survey (1915), pp. 807-808.

73/ Wyoming reference: *Mineral and Water Resources of Wyoming,* 86th Congress, 2nd session, Senate Document 76 (1960), p. 6; Utah reference: *Mineral and Water Resources of Utah,* 88th Congress, 2nd session, Committee Print (1964), p. 90.

74/ A. H. Koschmann and M. H. Bergendahl, "How About Gold?" *Mining World* (January 1961), pp. 26-28.

75/ T. A. Rickard, *op. cit.,* pp. 192-196.

76/ United States Bureau of Mines, *Minerals' Yearbook* (1949), p. 567.

77/ J. V. Beall, "Southwest Copper – A Position Survey," *Mining Engineer* (July 1965), p. 164.

FOOTNOTES (Continued

78/ United States Bureau of Mines, *Minerals Yearbook* (1949), p. 568.

79/ T. A. Rickard, *op. cit.*, p. 353.

80/ United States Bureau of Mines, *Minerals Yearbook* (1949), p. 568.

81/ A. C. Spencer and S. Page, *Geology of the Santa Rita Mining Area, New Mexico*, U.S. Geological Survey Bulletin 859 (1935), p. 66.

82/ W. Lindgren, L. C. Graton, and C. H. Gordon, *Ore Deposits of the Tintic Mining District, Utah*, U.S. Geological Survey Professional Paper 107 (1910), pp. 23 and 242.

83/ B. S. Butler and G. F. Laughlin, *Ore Deposits of Utah*, U.S. Geological Survey Professional Paper 111 (1920), pp. 292, 346, and 408.

84/ D. F. Hewett, *Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada*, U.S. Geological Survey Professional Paper (1931), p. 72.

85/ F. L. Ransome and J. L. Kellogg, "Quicksilver Resources of California," *California Journal of Mines and Geology*, October 1939, pp. 353-486.

86/ E. H. Bailey and D. A. Phoenix, *Quicksilver Deposits in Nevada*, Reno: University of Nevada (1944), p. 98.

87/ United States Bureau of Mines, *Minerals Yearbook* (1949), p. 514.

88/ R. D. Nininger, *Minerals for Atomic Energy*, Washington: U.S. Atomic Energy Commission (1955), pp. 2 and 4.

89/ J. L. Gillson, "Bentonite," *Industrial Minerals and Rocks*, New York: American Institute of Mining, Metallurgical, and Petroleum Engineers (1960), p. 90.

90/ D. E. Garrett and J. F. Phillips, "Sodium Carbonate from Natural Sources in the United States," *Industrial Minerals and Rocks*, American Institute of Mining, Metallurgical, and Petroleum Engineers (1960), p. 800.

91/ W. E. Ver Planck, *Boron in Mineral Commodities in California*, San Francisco: Division of Mines, Department of Natural Resources, Bulletin 176 (1957), pp. 89-90.

92/ Arthur F. Taggart, *Handbook of Mineral Dressing*, New York: John Wiley & Sons, Inc. (1927), p. 4-21.

93/ *Ibid.*, p. 4-55.

94/ R. H. Richards, *Ore Dressing*, New York: Hill Publishing Co., 2nd Edition (1908), p. 319.

95/ *Ibid.*, p. 39.

96/ *Ibid.*, p. 9.

97/ *Ibid.*, p. 336.

FOOTNOTES (Continued)

98/ *Ibid.*, p. 387.

99/ H. P. Woodward, State of New Jersey, Department of Conservation and Development, *Bulletin 57* (1944), p. 156.

100/ P. R. Hines and J. D. Vincent, *The Early Days of Froth Flotation: Froth Flotation,* 50th Anniversary Volume, A.I.M.E. (1962).

101/ R. H. Richards, *op. cit.*, pp. 494 and 644.

102/ T. A. Rickard, *op. cit.*, p. 338.

103/ C. H. Dunning, *op. cit.*, p. 198.

104/ C. G. Warnford Lock, *Economic Mining*, London (1895), pp. 415-464.

105/ R. P. Rothwell, ed., *The Mineral Industry: Its Statistics, Technology and Trade in the U.S. and Other Countries, From Earliest Times to the Close of 1893*, New York: Scientific Publishing Company (1893), pp. 287-298.

106/ *Ibid.*, pp. 272-283.

107/ Georgius Agricola, *De Re Metallica*, translated from the first Latin Edition of 1556 by Herbert C. Hoover and Lou H. Hoover, New York: Dover Publications, Inc. (1950), p. 354.

108/ L. S. Austin, *The Metallurgy of the Common Metals*, 2nd Edition (1909), p. 151.

109/ J. H. Taylor and P. F. Whelan, *The Leaching of Cupreous Pyrite and the Precipitation of Copper at Rio Tinto, Spain*, Institute of Mining and Metallurgy, Bulletin 457, pp. 1-36.

110/ H. F. Julian and E. S. Smart, *Cyaniding Gold and SIlver Ores*, Charles Griffin and Company, Limited, 2nd Edition (1913), pp. 1-7.

111/ A. F. Taggart, *op. cit.*, p. 12-03.

112/ Otis Young, *How They Dug Gold*, Tucson (1967), p. 124.

113/ C. G. Lock, *op. cit.*, pp. 526-528.

114/ *Ibid.*, pp. 515-555.

115/ *Ibid.*, pp. 639-651.

116/ T. A. Rickard, *op. cit.*, p. 338.

117/ R. P. Rothwell, ed., *op. cit.*, p. 458.

118/ A. F. Taggart, *op. cit.*, p. 342.

FOOTNOTES (Continued)

119/ C. G. Lock *op. cit.*, p. 298.

120/ *Ibid.*, p. 165.

121/ R. P. Rothwell, ed., *op. cit.*, p. 519.

122/ C. G. Lock, *op. cit.*, p. 264.

123/ E. P. Pfleider, ed., *Surface Mining,* New York: American Institute of Mining, Metallurgical, and Petroleum Engineers (1968), pp. 3-13.

124/ F. L. Wideman, "Copper," *Mineral Facts and Problems,* U.S. Department of the Interior, Bureau of Mines Bulletin 630, p. 279.

125/ E. P. Pfleider, *op. cit.*, p. 522.

126/ *Ibid.*, p. 524.

127/ *Ibid.*, p. 510.

128/ *Metal Mining Practice,* U.S. Bureau of Mines Bulletin 419 (1939), p. 35.

129/ H. W. Shiffer and LaMar G. Evanc, *Copper Leaching Practices in the Western U.S.,* U.S. Bureau of Mines Information Circular 8341 (1968).

130/ *Ibid.*

131/ U.S. Bureau of Mines, *Mineral Facts and Problems,* Bulletin 630 (1965), pp. 829-830.

132/ J. S. Anderson and M. S. Ritchie, "Solution Mining of Uranium," *Mining Congress Journal,* Vol. 54, No. 1 (January 1968), pp. 20-23, 26.

133/ U.S. Bureau of Mines, *Mineral Facts and Problems,* Bulletin 630 (1965), pp. 905-906.

134/ Newton, *op. cit.*, p. 93.

135/ R. W. Lewis, *Potassium Mineral Facts and Problems, 1965,* Dept. of the Interior, Bureau of Mines (1965), Bulletin 630, p. 723.

136/ *Ibid.*

137/ D. E. Garrett and J. F. Phillips, *op. cit.*, pp. 803-807.

138/ Thrush, *op. cit.*, p. 931.

139/ *Ibid.*, pp. 905-1100.

140/ *Ibid.*, p. 937.

141/ *Ibid.*, p. 1033.

142/ Agricola, *op. cit.*, p. 354.

FOOTNOTES (Continued

143/ Newton, *op. cit.*, p. 478.

144/ Thrush, *op. cit.*, p. 259.

145/ E. R. Ruhlman and G. E. Tucker, *Phosphate Rock Industries in 1954*, U.S. Bureau of Mines Mineral Market Report 2432 (1955), pp. 6-8.

146/ Charles Hillinger, "Gold Miner in the Sky One of Big Producers," *Washington* (D.C.) *Post*, February 13, 1969, p. A17.

147/ *Engineering and Mining Journal*, Vol. 169, No. 12 (December 1968), p. 77.

148/ Spenst M. Hansen and Alan R. Jagar, "How to Make Ore From Marginal Deposits," *Engineering and Mining Journal*, Vol. 169, No. 12 (December 1968), p. 75.

149/ Eugene P. Pflieder, *op cit.*, p. 954.

BLM Library
Denver Federal Center
Bldg. 50, OC-521
P.O. Box 25047
Denver, CO 80225

Bureau of Land Management
Library
Bldg. 50, Denver Federal Center
Denver, CO 80225

Bureau of Land Management
Library
Bldg. 50, Denver Federal Center
Denver, CO 80225